Production Note

LECTURES

ON SOME OF THE

PHYSICAL PROPERTIES OF SOIL

HENRY FROWDE, M.A.

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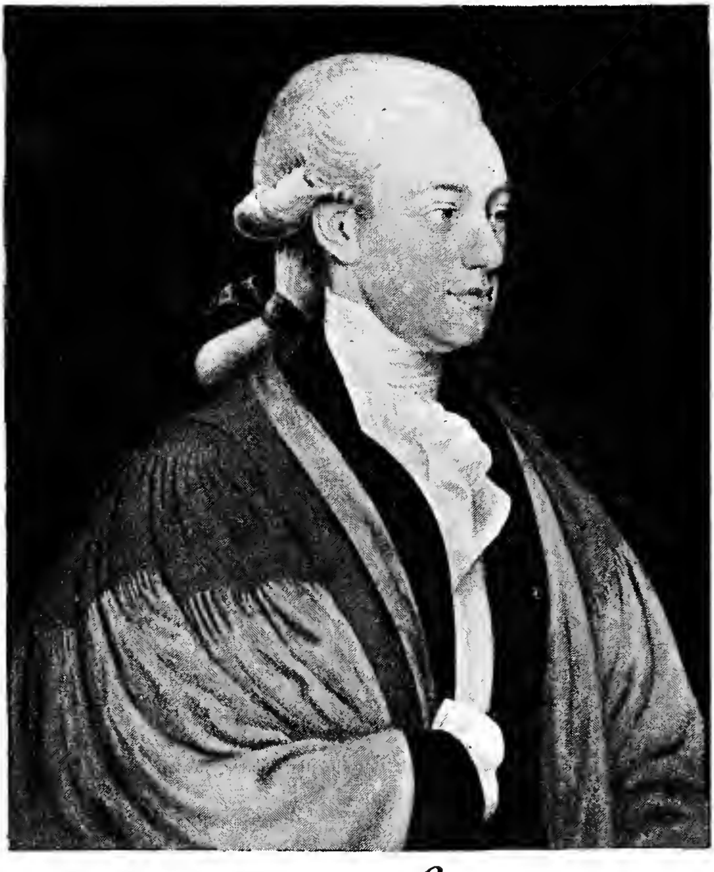

Joannes Sibthorp.

LECTURES

ON SOME OF THE

PHYSICAL PROPERTIES OF SOIL

BY

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WITH A FRONTISPIECE

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PREFACE

THE contents of this volume formed the substance of a course of lectures delivered by the author as Sibthorpian Professor of Rural Economy in Michaelmas Term, 1896. The subject of the final chapter did not actually form part of these lectures, though it had been prepared for delivery if time permitted. The whole of the matter has since been carefully revised.

The form of lectures has not been adhered to in the present volume; the language has in fact been greatly condensed. The title of lectures has, however, been retained, as it best expresses the character of the work. This is not a textbook, dealing exhaustively with the physical properties of soils; but lectures, discussing with some fullness particular portions of the subject.

In these lectures the attempt has been made to treat every subject from an experimental point of view, and a considerable space will be found occupied by accounts of the investigations which appear to have thrown most light upon the subjects discussed.

The behaviour of actual soils under known conditions has been made as far as possible the foundation of the conclusions drawn.

A great mass of results has accumulated from the investigations made in the very numerous Agricultural Experiment Stations in Europe and America; with these results the agricultural teacher is too often unacquainted. His valid excuse is the scattered publication of the reports, and his want of time to correlate the several results recorded. The writer hopes that the publication of these lectures will stimulate others to labour in the abundant harvest field of Experiment Station Reports. It must ever be borne in mind that it is only on the results of experimental investigations that Agricultural Science can be safely built.

The reader will probably be surprised that so little is said respecting English soils, and so much respecting the soils of America. The writer heartily wishes that this might have been otherwise. In fact, however, the physical constitution and properties of English soils have as yet not been investigated, save in a very few exceptional cases; this has been doubtless due to the great lack of investigators and research laboratories in this country. The general properties of soils can of course be equally well illustrated by any well studied examples, but the deficiency of knowledge of our own local soils is nevertheless a very real evil, and must greatly hinder the practical application of general principles.

The following pages will show the author's special indebtedness to the writings of Hilgard, King, Wollny, Mayer, Schloesing, and Lawes and Gilbert. The splendid work of Hilgard upon the soils of Mississippi and California must be regarded as in many respects a typical investigation; it needs to be repeated in every English county.

The frontispiece to the present volume is the portrait of John Sibthorp, M.D., F.R.S., Sherardian and Regius Professor of Botany in the University of Oxford; it is copied from the oil painting in the Botanical Library. Dr. Sibthorp was the founder of the Chair of Rural Economy in the University. He died in 1796, after a short life spent in active research.

Should the present volume meet with a favourable reception, it is the author's intention to publish a continuation of the work, in which some of the chief points in the chemistry of soil may be discussed on a similar plan.

R. WARINGTON.

Harpenden, October, 1899.

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INTRODUCTION

The physical properties of soil, and their bearing upon its fertility, is a subject which has been much neglected by the scientific investigator till quite recent years. The horticulturist and farmer have indeed from the earliest times realized the immense importance of a favourable texture of the soil, if crops were to be successfully grown. The special suitability of certain soils for certain crops, and the striking results which can be produced by skilful tillage, have always formed part of the inherited experience of agricultural art. In works dealing with practical agriculture, tillage operations have always occupied a prominent place.

The only early investigation on soil physics is that of Schübler, made more than sixty years ago. His work was comprehensive in its scope, and in general very accurate. At the present day his results still furnish some of the favourite quotations of our agricultural textbooks.

The rapid rise of agricultural chemistry in the middle of the present century diverted attention from the importance of such investigations. When it was realized that a chemist could analyse a crop and ascertain the elements of which it was composed, and then analyse the soil and ascertain what

proportion of these elements it contained, it was felt that the causes determining fertility were now at last firmly grasped. The large increase in the supply of artificial manures helped forward these novel views by making their practical application easy. At the present day agricultural chemistry still to a considerable extent monopolizes the field, although a fuller knowledge of the facts of agriculture has not borne out the theory to which we have referred. The part of agricultural science which is most prominently brought before our farmers in rural classes and lectures is still the need and application of artificial manures.

There can be no doubt that the neglect of the physical conditions of the soil as a subject of study, and in consequence as a subject of teaching, has done much to hinder the appreciation of science by practical men. The experienced farmer knows the overwhelming importance of a proper texture of the soil for the profitable culture of each crop. His scientific teacher has, however, little to say on this subject, while he freely recommends the use of expensive manures which a proper culture of the soil might render unnecessary, and which must fail to yield a profitable return if a favourable physical condition of the soil is absent. The farmer feels that this teaching is out of touch with the experience he has gained on the farm; he also frequently finds that the plan suggested is not a financial success. He therefore characterizes the advice given as 'theoretical,' and concludes that science is not a safe guide for the farmer.

A soil may be rich in all the elements of plant food, and yet be quite infertile. If seeds are to germinate in a soil, or if roots are to develop in a healthy and vigorous manner, there must be a suitable soil climate. The conditions as to

air, moisture, and temperature within the soil are quite as essential for vigorous plant growth as are the corresponding conditions in the atmosphere above.

Different crops, and even different varieties of the same crop, demand quite different degrees of moisture or dryness in the soil to bring them to perfection. The most favourable proportion of water varies even in the different stages of a plant's growth. The temperature of the soil required for various purposes is also very different. A knowledge of these facts is quite essential for deciding what crops should be grown upon a particular soil, and what treatment the soil should in each case receive for their successful culture.

The texture of the soil also largely determines the availability of the plant food which it contains. The surface presented to the action of the roots is far greater when a soil is in a condition of fine tilth, than when the same soil is consolidated, or contains unbroken clods. The supply of air and water, and the condition as to temperature, also largely determine the intensity and character of the chemical processes which take place in the soil, and by which plant food may be either produced or destroyed.

The movements of salts in a soil are to a large extent determined by physical actions, and on the extent and direction of these movements the effects produced by these salts will greatly depend. The fertilizing action of a saline manure, or the injurious effect produced by the accumulation of salts in alkali lands, is thus largely governed by physical conditions, and these conditions come more or less under the farmer's control when he is fully acquainted with their nature.

In most cases a good deal may be done to improve the physical conditions of a soil, and render it more suitable for

the production of the desired crop. It is possible to increase the retentive power of a soil for water, and to diminish the evaporation of the water it already contains. It is equally possible to reduce the amount of water in a soil which is naturally too wet. The surface temperature of the soil can also be increased in spring and summer by lessening its contents of water. Both the consolidation of the soil, and the loosening of its particles till they become a fine powder, are to a considerable extent under the farmer's control. By skilful management the salts of alkali lands can be prevented from rising to the surface and becoming a source of mischief. In every case a knowledge of the physical properties of the soil, and of the physical actions which go on within it, places them more or less under our control.

The overwhelming importance of the physical conditions of plant growth is perhaps most strikingly seen in the case of sandy soils extremely poor in plant food, which, nevertheless, from their extremely favourable physical condition, and the equally favourable climate of the locality, are soils of high agricultural value. Such an example is furnished by the narrow band of sandy soil in the State of Florida now devoted to the cultivation of pine-apples. This sand is almost entirely destitute of plant food, yet it responds so abundantly to the capital invested in it that the planted land has become worth from £100 to £500 per acre.

It is clear then that we must not judge of the value of a soil by the result of its chemical analysis; we must take its physical properties also largely into account. Indeed, in a majority of cases, the physical properties and climate will do more to determine its fertility than its chemical composition.

In recent years much has been done both in Germany and in the United States of America to increase our knowledge of the physical properties of soils. Since 1878, a periodical edited by E. Wollny, *Forschungen auf dem Gebiete der Agriculturphysik*, has been devoted to the publication of papers on this subject. In America the study of the soils characteristic of several States and districts has been energetically carried on by Hilgard, and with a more limited scope by King. Since 1893, the subject has been taken up by the U. S. Department of Agriculture, at first in connexion with the Weather Bureau, and since 1895 under a separate Division of Agricultural Soils, superintended by Professor M. Whitney. The inquiry which was at first local has thus grown to be one of national application. The facts available for a discussion of the subject have thus become very numerous. Some of the investigations made, and some of the conclusions arrived at, will be found in the following pages.

PHYSICAL PROPERTIES OF SOIL

CHAPTER I

PHYSICAL CONSTITUTION OF SOIL

Physical Constitution of Soil—Methods of Mechanical Analysis—Relation of Physical Constitution to Fertility—Tenacity of Soil—Cementing Materials in Soil—Coagulation of Clay—Shrinkage on Drying—Nature and Origin of Tilth—Specific Gravity of Soil—Weight of Soil per Acre—Colour of Soil—Odour of Soil.

Physical Constitution. A soil is a mass of solid particles, differing in their size, shape, and nature. In approaching the subject of the physical constitution of soil it is simplest to take, in the first instance, the case of an ideal soil, consisting of uniform particles, having all the same size, shape, and nature. In a system composed of solid spheres the number of particles in any given volume will depend firstly on the size of the particles, and secondly on their mode of packing. If the spheres are all of the same diameter, there will be a closest and a loosest mode of packing, in each of which every particle is in contact with all those surrounding it; such arrangements are shown in Fig. 1.

In both these systems of spheres there is clearly a considerable proportion of empty space between the particles, which only touch each other at certain points. With the closest packing the interspaces form 25·95 per cent. of the total

volume of the mass; with the loosest packing the interspaces are 47·64 per cent. of the total volume.

The proportion of the volume occupied by interspaces, though varying so much with the mode of packing, is quite independent of the size of the particles, so long as all the particles are of one size. Thus, if a single spherical marble, one inch in diameter, be placed in a square box having an internal capacity of one cubic inch, the unoccupied space will be 47·64 per cent. of a cubic inch. If the same box is now

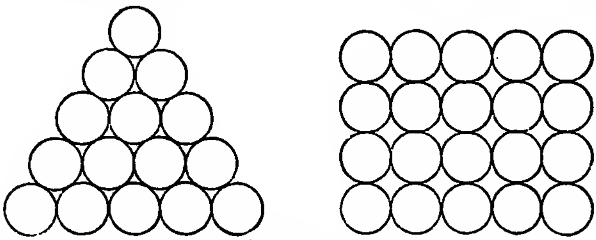

FIGURE 1.

filled with one million marbles, each of $\frac{1}{100}$th inch in diameter, the packing being of the loosest description already referred to, the unoccupied space will again be 47·64 per cent. of a cubic inch[1]. In the second case the interspaces are individually far smaller than in the first case, but their united volume forms the same proportion of the whole. This is an important fact to bear in mind. The proportion of interspaces in a soil plainly determines both the volume of air which the soil will contain when dry, and the volume of water which it will hold when fully saturated. In a coarse sand, and in a fine clay, the maximum capacity for air and water will be the same, if each is composed of uniform particles packed in the same way.

[1] This, and several other illustrations in this chapter, are taken from Professor King's very interesting book *The Soil*.

If the particles composing a soil are not all of one size, but are a mixture of large and small, then the proportion of interspaces in the whole volume is diminished, the small particles fitting in between the large ones. If in the system of solid spheres with closest packing, a second set of spheres is introduced, exactly fitting into the spaces between the larger ones, the proportion of the interspaces will be reduced from 25·95 to 6·76 per cent. of the total volume. If the process is repeated by the introduction of a third set of still smaller spheres, exactly fitting the remaining spaces, the proportion of interspace will fall to 1·76 per cent. of the total volume (Soyka, *Wollny's Forsch. der Agrikulturphysik*, 1885, 1). Any mixture of particles of different size—and all soils consist more or less of such mixtures—tends therefore considerably to reduce the space available for air or water.

If, on the other hand, the particles composing a soil are themselves porous, the volume of the interspaces may be considerably increased. It is indeed obvious, that if spheres of sponge were substituted for the solid spheres in the systems represented in Figure 1, the proportion of unoccupied space in the total volume would become very much greater. The particles of quartz sand in a soil are non-porous, but particles of limestone are generally porous, and the particles of decayed vegetable matter (humus) are highly porous. A fertile soil also largely consists of compound particles, made up of fragments of various sizes, held loosely together; such particles act as large particles in the soil, but are themselves porous. The proportion of empty space in a mass of soil may also be greatly increased by appropriate tillage operations, the object of which is to bring the soil into a state of loose powder, thus increasing its bulk. The condition of a fertile

soil, rich in humus, and possessing a good tilth, is thus one attended with a large proportion of interspaces. We shall go into further details on these points when we treat of the capacity of soils for water.

Another important fact is plainly taught by the system of solid spheres which we have taken as the simplest example of a soil. Although the size of the spheres is without influence on the proportion of the interspaces, it has an enormous influence on the extent of surface which the spheres present. In the case of the spherical particles contained in one cubic inch, we have the following variations in surface brought about by alterations in the size of the spheres.

Number of spheres in 1 cubic inch.	*Diameter of each sphere.*	*Total surface of spheres contained in 1 cubic inch.*
One	1 inch ...	3·1416 square inches
A thousand	$\frac{1}{10}$ inch ...	31·416 ,,
A million	$\frac{1}{100}$ inch ...	314·16 ,,
A thousand millions ...	$\frac{1}{1000}$ inch ...	3141·6 ,,
A million millions ...	$\frac{1}{10000}$ inch ...	31416 ,,

A solid mass of matter, reduced to particles of $\frac{1}{10000}$th its former diameter, has thus its surface increased ten thousand times.

The extent of internal surface possessed by a soil thus depends on the fineness of the particles of which it is composed, and is immensely greater in the case of a clay soil than in the case of a coarse sand. King has calculated, that in the case of a soil composed of particles $\frac{1}{1000}$th inch in diameter, a cubic foot of soil will possess an internal surface of about one acre. Soyka states, that in one litre of spherical particles 0·01 mm. in diameter, the total surface will be 444·0 square metres with the tightest packing, and 314·4 square metres with the loosest packing. The internal surface

of a soil is of course increased when the particles composing it are themselves porous.

Many of the most important properties of soil depend on the extent of the internal surface. We must always bear in mind that the whole of the work done by the solid matter of a soil takes place on the surface of its particles. The retentive power of a soil for water is determined almost entirely by the extent of its internal surface; the retentive power of a soil for manure is influenced also by the same circumstance. With an increase in the internal surface the feeding ground of the roots of plants is also plainly increased.

An increase in the fineness of the particles beyond a certain point is, however, attended with disadvantages. The cohesion between the particles of a soil is enormously increased by an increase in their surface. The resistance to tillage, and the resistance to the passage of roots becomes greater, and the soil is said to be 'heavy.' A soil composed of very fine particles is also with difficulty permeable to either water or air, owing to the immense friction which attends the movement of any fluid through the minute interstices between the particles. We shall return to this subject in detail further on, at present we may just mention that the greatest number of advantages are secured when the internal surface is large, but the soil consists mainly of porous compound particles, the size of which allows any excess of water to be removed by drainage.

Mechanical Analysis. The physical properties of a soil are largely dependent on the size of the particles of which it is composed. Every one recognizes at once the immense difference there is between a coarse sand, a loam, and a clay; the differences between these soils, which so greatly influence

their fertility, and which demand in each case a distinct treatment by the farmer, are primarily due to the differences in size of their respective particles.

From the time of Schübler down to the present day the soils most commonly occurring have been described and classified as if they consisted essentially of various proportions of *two* constituents, one composed of coarse, the other of fine particles, namely *sand*, and *clay*. His definitions of clay, loam, and sandy soils (Schübler, *Grundsätze der Agricultur-Chemie*, 1838; also *Jour. Roy. Agri. Soc.* 1842, 156) were as follows:—

	Percentage of Clay.	*Percentage of Sand*[1].
Argillaceous soils ...	above 50 ...	below 50
Loamy soils	30–50 ...	50–70
Sandy Loams	20–30 ...	70–80
Loamy Sands	10–20 ...	80–90
Sandy soils	below 10 ...	above 90

In modern Textbooks the proportions of sand and clay assigned to the various soils named above often differ a good deal from those given by Schübler, but in nearly every case the principle of classification is the same, the soils being always assumed to be composed of varying proportions of *two* constituents.

This simple view of the constitution of soil is unfortunately both inaccurate and impracticable. Soils do not consist of particles of two sizes; they consist of particles exhibiting a very wide range of size, and the preponderating groups of particles in different soils occur in very different parts of this series. The separation of the constituents of a soil into two groups—sand and clay—is also impracticable, as there is no

[1] When the soil contains lime or humus the proportion of sand will be correspondingly diminished.

natural division between them, what is called clay consisting for the most part of extremely fine sand. Any separation into sand and clay is thus purely arbitrary, and the results obtained depend entirely on the method adopted. Moreover analysts have never agreed on any definition of sand and clay, nor have they adopted one general method for their estimation. The results arrived at by the older methods of separation have thus no definite value, while they at the same time afford no true representation of the constitution of the soil analysed.

The aim of the mechanical analysis of a soil is to determine the proportion of its different physical constituents. Its scope is generally limited to determining the proportion of particles of different sizes; but in some schemes this scope is enlarged to include a determination of the calcium carbonate and humus in each group of particles. As the particles which make up a soil have an almost infinite variety of size, all that can be done is to group them, by placing all that lie between two dimensions in one group. We thus naturally find both simple and more elaborate plans of analysis, in which the constituents are arranged in few or in many groups, the latter of course giving a more accurate view of the constitution of the soil. The names commonly given to these various groups—as Stones, Gravel, Grit, Coarse Sand, Fine Sand, Silt, Clay—are very indefinite, and refer to particles of very different size in different schemes of analysis. The statement that a soil contains so much fine sand, or so much clay, is thus of very little value, unless the mode of analysis is also mentioned. On the other hand the physical characters of a group of particles—their diameter, or hydraulic value—are perfectly definite, and are much to be preferred for

scientific purposes to the uncertain names already mentioned. The following classification of soil constituents given by Wollny (*Exp. Station Record*, vi. 762) will afford a good idea of the divisions now made in the more complete methods of soil analysis.

	Diameter of Particles.
1. Stones	over 10 mm.[1]
2. Coarse Gravel[2]	5 - 10 mm.
3. Medium Gravel	2 - 5 mm.
4. Fine Gravel	1 - 2 mm.
5. Coarse Sand	0.5 1.0 mm.
6. Medium Sand	0.25 - 0.5 mm.
7. Fine Sand	0.1 - 0.25 mm.
8. Coarse Silt	0.05 - 0.1 mm.
9. Medium Silt	0.025 0.05 mm.
10. Fine Silt	0.005 - 0.025 mm.
11. Clay	0.0001 - 0.005 mm.

In a mechanical analysis the coarser groups of particles are separated by means of metal sieves with circular holes; the smallest diameter of hole which can be practically used is 0·5 or 0·25 mm. With the finer sieves the soil is used in a wet state, and the work aided by a gentle stream of water. The residue remaining on each sieve must be thoroughly washed with water, and if necessary rubbed with a soft brush, to separate any adhering finer matter. If the soil contains much clay, the separation is greatly aided by previously boiling the soil with distilled water for several hours. Should however the coarse particles be composed of slate, or other soft material, the boiling will disintegrate

[1] A millimetre is about $\frac{1}{25}$ inch; it is the most convenient unit of length for small dimensions.

[2] The terms gravel, sand, &c., used for designating the physical constituents of a soil are to be understood as expressing the size and not the nature of these constituents. The sand, for instance, may consist of quartz, of felspar, of limestone, or of a variety of other materials.

them and lead to erroneous results. In this case unboiled soil must be used, and the matter retained by the sieves lightly rubbed under water with the finger, or a caoutchouc pestle, till the water ceases to become turbid.

The finer groups of soil constituents, which pass through the sieve with narrowest meshes, are separated by elutriation. The methods which have been employed are very numerous. Some are based on the fact that when soil has been shaken up with water the larger particles are the first to subside; in others the separation is effected by the successive use of streams of water of different velocities, the feeblest current removing only the finest particles.

A simple method of analysis, sufficing only to give a general idea of the character of the soil, is that recommended by Schloesing; it is employed in France, Belgium, and Italy. Full details will be found in Schloesing, *Chimie agricole*, 1885, 80; Grandeau, *Traité d'Analyse*, 1897, 252; and Wiley, *Agricultural Analysis*, i. 200. The coarser ingredients, 'Pebbles' and 'Gravel,' are separated by sieves with 5 mm. and 1 mm. meshes, the separation of these in a clean state being aided by water.

The fine soil and water which has passed through the 1 mm. sieve is allowed to stand twenty-four hours, the clear water is then decanted, and the remaining soil and water evaporated till the mass assumes the condition of a stiff paste, which is then carefully kneaded by the fingers till it has a perfectly uniform composition. Water is determined in a portion of this paste, and two other portions, each representing about 10 grams of dry soil, are taken for a duplicate analysis. Each portion is placed in a porcelain capsule 9–10 cm. diameter, 15–20 cc. of water added, and the whole stirred with the

finger. After ten seconds the turbid water is decanted, and the operation repeated till the water runs off clear and the sand remains clean; this is then dried and weighed. It is called the 'coarse sand.' The turbid water which has been decanted is then acidified with nitric acid and allowed to stand till all calcium carbonate is dissolved[1]; the whole is thrown on a filter, and the residue washed with distilled water till all lime is removed. The fine soil is then washed off the filter with distilled water into a two-litre beaker, and 2 cm. of ammonia added to dissolve humic matter. After three or four hours the whole is diluted with distilled water to two litres, well stirred, and allowed to stand twenty-four hours. The matter still in suspension is then removed by a syphon. The sediment is again treated with 2 cc. of ammonia, and again diffused in a litre of pure water, and after twenty-four hours the water is decanted. If the decanted water is distinctly turbid the treatment must be again repeated. The sediment is finally dried and weighed; it is reckoned as 'fine sand.'

The clay left in suspension is precipitated by the addition of an acid[1], and collected on a filter. The filter when drained is placed on blotting paper, and by skilful manipulation when half dry the clay is pressed into a single cake, which is dried and weighed; the paper of the filter is burnt, and the ash added to the mass of clay before weighing.

By treating the stones and the coarse sand with dilute acid, any calcium carbonate they contain can be determined. The calcium carbonate occurring in the finer portion can be determined in the nitric acid solution mentioned above. By proceeding in this way the siliceous and calcareous matter

[1] The action of these reagents will be understood when we have spoken of the coagulation of clay, see p. 30.

in each separated portion of the soil can be ascertained, if this is thought desirable. It is of course equally possible to determine the amount of vegetable residue and humic matter in each of the separated parts.

The separation of the finest portion of the soil into two groups is also conveniently carried out by using the cylinders devised by Kühn and Knop (Wiley, *Agricultural Analysis*, i. 189). The soil having had its coarser ingredients separated by sieves, and having been well boiled, is introduced into a tall cylinder, which is then filled with water and well shaken. After a certain number of minutes, a side tube is opened and the turbid water allowed to flow out, and the operation is repeated till the water runs clear.

The methods we have just mentioned do not attempt to separate all the particles of a soil into groups of definite size or character. The two American methods we shall next describe yield far more complete results.

In Osborne's method (*Rep. Exp. Station, Connecticut*, 1886, 141; 1887, 144; 1888, 154. Wiley, *op. cit.*, 196) the separation of particles of different sizes is effected by a graduated subsidence, as in the methods already noticed; but the whole operation is controlled by a microscopic measurement of the largest and smallest grains in each sediment, so that the portions finally weighed are known to consist of particles the diameters of which fall within the limits laid down in the scheme. It must be borne in mind however, that any group of particles obtained by subsidence will not be entirely of the same size in cases where the soil particles consist of substances having different specific gravities. This being inevitable, the character of the group is fixed in every case by the diameter of the quartz particles only. The same

difficulty arises when soil particles are separated by currents of water of definite velocity, the specific gravity of the substance affecting the size of the particle which is removed by the current.

Osborne takes 30 grams of soil which has passed through a 3·0 mm. sieve. By the aid of water the soil is passed successively through sieves having circular holes of 1·0, 0·5, and 0·25 mm. diameter. By fractional subsidence in water the still finer particles are then divided into four groups of diameters ·05–·25 mm. (*fine sand*); ·01–·05 mm. (*silt*); below ·01 mm. (*dust*); matter not deposited in twenty-four hours (*clay*). The clay may be precipitated by adding ammonium nitrate to the water. Osborne's method answers well for the amount of separation just described, but is not convenient when a more detailed analysis is required.

The methods making use of currents of water of different velocity to separate the variously sized particles are numerous; the most satisfactory is that of Hilgard (*American Jour. Science and Art*, 1873, 288, 333; *California Exp. Station Report*, 1891–92, 248; Wiley, *op. cit.*, 225). He removes the coarser constituents of the soil by sieves, the finest sieve having meshes 0·5 mm. in diameter. Of the sifted soil, 10 or 15 grams are boiled in a narrow-necked sloping flask for 8–15 hours, the contents transferred to a beaker, diluted to about 1½ litre, well mixed, and allowed to stand a short time till the particles of 0·25 mm. per second hydraulic value, with all heavier particles, have deposited. The turbid water is then decanted, and the sediment again stirred up with water, and again allowed to settle; and this treatment is repeated till the water comes off clear. The united turbid water is well mixed, and any deposit occurring in a short time is added

to the previous sediment; this precaution is necessary, as the first clay water may have been sufficiently strong to hinder by its viscosity the subsidence of the coarser particles.

We now have the soil divided into two portions, 1. the mixed sediments; 2. the turbid water containing the finest silt and clay. The turbid water is now allowed to stand in a cylindrical vessel, 20 cm. in height, from twenty-four to sixty hours, till all silt has deposited. The clay water is then decanted. The sediment is rubbed with a caoutchouc-covered pestle, well mixed with water, and the whole again allowed to stand for twenty-four hours, and this treatment is repeated till the sediment is free from clay; it can then be dried and weighed. This sediment corresponds with Group No. 12 in Table I. The clay is then precipitated by adding 50 cc. of saturated brine to each litre of clay water. The clay falls as a gelatinous precipitate; it is collected on a weighed filter, washed with weak brine, dried and weighed. The filter containing the dried clay is then replaced in the funnel, and well washed with a weak solution of ammonium chloride. The washings are evaporated to dryness, the residue heated to expel ammonium chloride, and weighed. The combined weight of the paper, and of the sodium chloride obtained in the last operation, is deducted from the previous weight of the filter and contents, thus giving the weight of the clay.

The mixed sediment, containing all except the finest constituents of the sifted soil, is next introduced into Hilgard's churn elutriator, and separated by currents of water of definite velocity into nine groups. The construction of the elutriator is shown in Fig. 2. The drawing is taken by permission from Wiley's *Agricultural Analysis*.

The elutriator consists of an upright glass cylinder, 300 mm.

in height and 45 mm. in diameter; this cylinder is united at its lower end to a brass cup-shaped funnel, crossed by an horizontal axis furnished with four wings; this churn is separated from the cylinder by a wire screen with meshes 0·8 mm. in diameter. The churn is worked by any convenient motor power; about 500 revolutions per minute is the speed required when separating the two finest groups of particles, for the other separations a smaller velocity will suffice. The

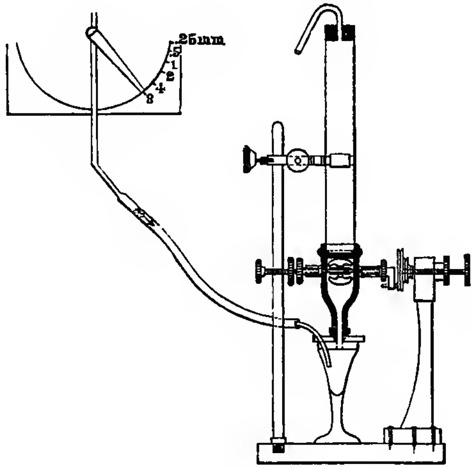

FIGURE 2.

lower end of the brass funnel is fixed into a conical test-glass, which is in connexion with the water supply. The water is supplied from a reservoir maintained at a constant level. The lever opening the water tap moves over a graduated arc, on which are marked the positions of the lever which yield supplies of water giving the required velocities in the glass cylinder.

The apparatus being half filled with water, and the churn

in motion, the sediment is introduced, and the water current adjusted to the lowest velocity, 0·25 mm. per second; this current is continued till the water ceases to remove any more matter. The operation requires many hours for its completion. The object of the churn is to break up the aggregations of fine particles which are very apt to form. Should any be seen on the sides of the cylinder, the apparatus must be stopped, and the flocks detached with a feather. The water leaving the cylinder is conducted by a tube nearly to the bottom of a tall wide vessel, from the top of which the water runs to waste. The receiving vessel being much wider than the separating cylinder, the upward current of water in it is too slow for any of the solid matter carried into it to escape.

When no more particles are removed by the current moving 0·25 mm. per second, the receiver is changed, and the velocity of the current increased to 0·5 mm. per second. When the second group of particles has been in this way removed, the velocity of the current is again doubled, and this mode of proceeding is continued till the last separation with a velocity of 64 mm. per second is completed. With velocities above 4 mm. per second the churn may be dispensed with. The work gets more rapid as the higher velocities are reached. When the apparatus is in action day and night the separations will be completed in three or four days. Soft filtered water should be used in all the operations.

In all modes of separation the greatest difficulty is met with when dealing with the finest constituents. The silt obtained by subsidence from the clay water always carries down clay with it, and can only be freed by rubbing with a caoutchouc pestle and resubsidence from water many times

repeated. The clay water finally obtained also contains more than one group of matter. Subsidence for twenty-four hours will remove all particles of sand exceeding ·005 mm. in diameter, but much of a still finer nature will remain suspended with the true clay.

True colloid, jelly-like clay, forms according to Schloesing a very small proportion of the clay obtained by the method just described. To obtain the colloid clay he precipitates the clay water with weak acid; the clay is then collected on a filter, and washed with distilled water. When removed from the filter the clay is treated with a small quantity of ammonia, and finally diffused in a considerable volume of distilled water. The whole is then left for weeks or months till all deposit ceases. The microscope can then no longer detect particles of visible dimensions in the solution. The colloid clay may then be precipitated by the addition of an acid; it dries to a translucent, horn-like mass. According to Schloesing the true colloid clay forms seldom more than 1·5 per cent. of the stiffest natural clays.

Besides colloid clay, the clay water contains the other colloid bodies (hydrogels) present in the soil; the commonest of these are humic acid, humates, hydrated silicates (zeolites), and hydrated ferric oxide; hydrated silicic acid and hydrated alumina are less frequent constituents.

We must then always regard the clay in a mechanical analysis of soil as a mixed group containing the finest particles in the soil, but the precise nature of which will vary in different soils, and will also depend on the method of analysis adopted.

The methods used for the mechanical analysis of soil give their sharpest results with soils containing but little humus.

Hilgard always prefers to use a sample of the subsoil collected immediately below the surface. The subsoil has moreover the further advantage of being more uniform in character than the surface soil. When humus is present, its total amount should be determined in the sample prepared for analysis, and the humus present in the various separated portions must be deducted from their weight. Osborne states that boiling has little effect in disintegrating the particles of a soil held together by humates, and that rubbing with a caoutchouc pestle is in this case distinctly preferable. The sum of the products of the mechanical analysis of a soil generally exhibits a small loss, due to the removal of soluble matter by the water.

Relation of Physical Constitution to Fertility. We will now proceed to give examples of the physical constitution of soils, as determined by the more accurate methods just described. Our first examples (Table I) shall be selected from Hilgard's splendid series of analyses of the soils of Mississippi (*Proc. American Ass. Advancement Science*, 1873). The soils had been sifted through a 3·0 mm. sieve before analysis.

The pipe-clay is an example of a very pure natural clay; it is seen to have a very simple composition, the two finest groups of constituents making up more than 95 per cent. of the whole.

The clay subsoil No. 1 is of tertiary origin. It is a heavy intractable soil on which water will stand for weeks. It is very difficult to till, and yields good crops only in favourable seasons, as it is injured both by drought and excessive rain. The composition is simple, the three finest groups of particles forming 84 per cent. of the whole.

The clay subsoil No. 2 is of similar origin to No. 1; it is however more easily tilled, and is a productive soil. The

TABLE I

PHYSICAL ANALYSES OF MISSISSIPPI SOILS (HILGARD)

No.	Names of Constituents.	Hydraulic Value mm. per sec.	Diameter of Quartz Grains mm.	Pipe-clay.	Heavy Clay Subsoils.		Loam Subsoil.	Sandy Loam.		River Deposit.	Sandy Soil.
					1	2		Subsoil.	Soil.		
1	Grit		1.0 –3.0		0.33	1.97	0.23	0.36	0.36		6.94
2	,, ...		0.5 –1.0		0.35			0.83	2.98		17.65
3	Sand	64	0.306–0.500			0.72	1.47	6.21	6.62	0.15	18.81
4	,, ...	32	0.166–0.306	0.06		2.32	2.33	3.38	7.75		10.16
5	,, ...	16	0.122–0.166			2.09	1.17	3.85	3.01		2.66
6	,, ...	8	0.077–0.122	0.08	0.23	0.70	0.78	1.49	1.59	3.74	1.66
7	,, ...	4	0.050–0.077	0.02	0.18	1.29	0.76	0.64	1.19	21.49	1.02
8	Silt	2	0.040–0.050	0.04	1.61	1.81	9.79	2.63	3.56	21.83	0.88
9	,, ...	1	0.028–0.040	0.08	2.66	3.60	7.26	5.40	6.50	14.01	1.96
10	,, ...	0.5	0.017–0.028	0.08	9.13	2.73	13.14	7.77	13.97	9.93	7.89
11	,, ...	0.25	0.011–0.017	2.00	26.64	13.30	15.07	16.65	14.20	9.58	8.40
12	,, ...		0.001–0.011	21.15	32.35	25.33	26.50	37.75	29.36	8.65	15.53
13	Clay			74.65	25.48	40.25	19.19	10.70	4.58	10.35	8.63
				98.16	98.96	96.11	97.69	97.66	95.67	99.73	102.19

analysis shows it to contain a good deal more clay than No. 1. Hilgard points out, however, that the heaviness of a soil is largely determined by the sum of the three finest constituents, the influence of which is further modified by the presence of coarse sand, lime, and ferric oxide. In the present soil 10·6 per cent. of ferric oxide, and 0·8 per cent. of lime were present, with some sand; the effect of these constituents was to reduce the tenacity of the clay.

The loam subsoil which stands next in the table represents a first-class upland cotton soil. It is pretty easily tilled, but suffers much from swelling in alternate frost and thaw, and from denudation during heavy rain, owing to its being not sufficiently pervious to water. The proportion of clay is here considerably reduced, but the soil is composed almost entirely of the finer constituents.

The sandy loam soil and subsoil belong to the drift period; they are characterized by the growth of the long-leaved pine. The soil is very light and easily tilled. We have come now to soils containing much less clay, and a considerable proportion of coarse sand. It will be remarked that the coarser constituents preponderate in the surface soil, and the finer constituents in the subsoil. This is a general fact in all soils from districts having a considerable rainfall; in the arid regions of the United States this difference is not observed. The preponderance of coarser particles in the surface soil is due to the gradual removal of the finest particles from the surface by rain water. Further illustrations on this point will be found on pp. 45–9.

The river deposit is a light, very porous soil, of great fertility, recently deposited by the Mississippi. It is largely composed of silt and very fine sand, the principal portion of

its constituents having almost the same hydraulic value. This deposition in one place of particles of a similar size is characteristic of the soils formed by rivers.

The sandy soil is from the uplands of Mississippi. It is of considerable fertility, but possesses so little cohesion that it loses its finer constituents in a high wind when left unprotected. Unlike the soils previously noticed, it is mainly composed of coarse sand.

A further very instructive example of the results obtained by a detailed mechanical analysis of soil is furnished by the analyses of certain typical subsoils in Maryland, published by Whitney (*U.S. Weather Bureau, Bulletin* 4; Wiley, *op. cit.*, 249). The separation in this case is into fewer groups than those in Hilgard's analyses.

TABLE II

PHYSICAL ANALYSES OF MARYLAND SUBSOILS (WHITNEY)

	Diameter of Particles mm.	1 Early Market Garden.	2 Market Garden.	3 Tobacco Land.	4 Wheat Land.	5 Wheat and Grass.	6 Grass and Wheat.
Fine Gravel . .	1.0 -2.0	0.49	0.04	1.53			1.34
Coarse Sand . .	0.5 -1.0	4.96	1.97	5.67	0.40	0.23	0.33
Medium Sand .	0.25 -0.50	40.19	28.64	13.25	0.57	1.29	1.08
Fine Sand . .	0.10 -0.25	27.59	39.68	8.39	22.64	4.03	1.02
Very fine Sand .	0.05 -0.10	12.10	11.43	14.95	30.55	11.57	6.94
Silt	0.01 -0.05	7.74	4.95	28.86	13.98	38.97	29.05
Fine Silt . . .	0.005-0.01	2.23	2.02	7.84	4.08	8.84	11.03
Clay	-0.005	4.40	8.79	14.55	21.98	32.70	43.44
		99.70	97.52	95.04	94.20	97.63	94.23

The early market-garden soil[1] is a light yellow sand,

[1] In American writings, market-garden soils are spoken of as 'truck land.'

having little power of retaining water; it is therefore characteristically warm and dry. With abundant dressings of farmyard manure, it produces spring-sown garden vegetables about ten days earlier than any other soil in the State. It is the coarsest soil in the series, and contains nearly 73 per cent. of coarse to fine sand.

The market-garden soil is of much the same character as the preceding, but it contains more clay, and the sand is of a finer description. Its power of holding water is greater, and it produces larger crops of vegetables than the previous soil, and is much superior to it for small fruits, peaches, and for autumn-sown crops; but the produce of spring-sown crops matures later than on the first soil.

The tobacco lands of Southern Maryland contain 10–20 per cent. of clay. The lighter soils yield the smallest crop, but the finest tobacco. Wheat is grown on tobacco land as part of the rotation, but the soil is too light for wheat to be made the principal crop.

The wheat land represents the lightest soil on which wheat can be profitably cultivated in the climate of Maryland. The soil is too light for permanent meadow or pasture, and too heavy for the best quality of tobacco. Market-garden crops are late in coming to maturity on this soil.

The wheat and grass land represents the heavier wheat soils; it is considerably more productive than the preceding, and is sufficiently retentive of water to make good grass land.

The grass and wheat land is an example of a still heavier soil lying on a limestone formation; it possesses considerable fertility.

This series of typical soils is most instructive; their composition ranges from soils consisting chiefly of coarse particles

to those in which the finest groups largely preponderate. With these differences in physical constitution, the agricultural value of the soils, and their suitability for the growth of different crops are plainly connected. We could hardly have a better illustration of the great influence of physical structure, and of the extent to which this can be revealed by the methods of mechanical analysis.

The alluvial soils, which cover large areas of the central and western States of America, are not represented in the above table. Ancient alluvial soils, often described as Loess[1], have, like their modern representatives (see River Deposit, Table I), a very simple constitution, the currents of water which brought them to their present resting place having deposited in one spot particles of similar hydraulic value. The Loess soils of Illinois and Nebraska contain according to Whitney (*Soils, Bulletin* 5, p. 13) from 50 to 70 per cent. of silt, the particles of which are mostly ·01–·05 mm. diameter. The so-called 'Plains Marl' of the same district in America is a soil of apparently similar origin, but composed of rather coarser particles; the samples examined by Whitney contained 71–75 per cent. of very fine sand, diameter of particles ·05–·10 mm. Both these kinds of soil contain but little clay, yet their water-holding power is considerable, and they make good wheat land. We shall see presently (p. 99) that it is in soils of this class that the capillary movement of water takes place to the most beneficial extent.

By assuming an average diameter for the particles in each of the separated groups, and knowing their specific gravity,

[1] The typical Loess of the Rhine is an extensive deposit apparently formed at the close of the glacial period. when the rivers in the northern hemisphere greatly exceeded their present bounds. The Loess of America has probably a similar origin.

it is possible to calculate approximately the number of particles contained in any given weight of soil, and to estimate their total surface area; this has been done by Whitney in the case of the soils mentioned in Table II. The number of particles in one gram of dry soil, and their surface area were as follows.

		Number of Particles in one gram.		*Surface Area of Particles.*
Soil 1	...	1958 millions	...	760 square centimetres
„ 2	...	3955 „	...	1008 „ „
„ 3	...	6786 „	...	1902 „ „
„ 4	...	10229 „	...	2493 „ „
„ 5	...	14736 „	...	3593 „ „
„ 6	...	19638 „	...	4575 „ „

The average diameter assumed for the particles of clay is of course very uncertain.

The above calculation assumes that all the ultimate particles in the soil are free, and not arranged so as to form compound particles, the existence of which would necessarily diminish both the number of particles and their available surface area. The figures given above are thus probably maxima, which are not actually reached in the respective instances. The calculation, however, shows in a striking manner the characteristic differences which exist between soils composed of coarse and those composed of fine particles.

The Tenacity of Soil. A fertile soil must possess a sufficient solidity, one of its functions being to afford a firm support to the plant, and enable it to withstand the force of wind and rain. It must not, on the other hand, offer too great an obstacle to the spread of roots. An open texture of soil is especially needed during the early growth of a seedling plant. A good arable soil should also allow of the easy use of tillage implements, and should break down readily when they are skilfully employed.

A farmer is accustomed to classify soils as light and heavy; this language is to be understood as referring to the resistance which they offer to tillage. A heavy soil is one of great tenacity, the particles of which are held together by a strong cohesive force. When such a soil is dug, or ploughed, great strength is required to perform the work, and the soil is therefore said to behave as if it were heavy. This resistance to the application of mechanical force is due to the cohesion and not to the weight of the soil, the weight of a cubic foot of wet clay is indeed much less than the weight of a cubic foot of sand.

A considerable degree of stability may be obtained when the individual particles of a soil are very large and heavy, as in the case of a coarse gravel; in such cases the stability is due to the weight of the particles, and not to any appreciable extent to the cohesion between them.

As the particles diminish in size, they become more easily moved, and we obtain blowing sands, such as are seen on our own Norfolk coast, and which occur to a serious extent in other countries. On the other hand, a decrease in the size of particles is attended with a large increase in their total surface, and sand exhibits a considerable degree of coherence when wet, though scarcely any when in a dry state.

When the particles become extremely fine, corresponding in fact to the groups described as silt in the physical analyses of soil already given, the cohesion of the mass when in a wet state is very similar to that exhibited by clay; the wet soil is in fact a sticky mud. Soils of this character are often spoken of as clay soils; their true nature becomes revealed when they dry, as they then easily fall to powder.

It is important to note that the coherence of silt, sand,

chalk, and humus is greatest when they hold sufficient water to fill up all the finer spaces between their particles. As these substances dry, they lose to a great extent the coherence they possessed when wet. Clay, on the other hand, increases greatly in coherence as it dries, and finally becomes a hard, solid substance. These are fundamental facts to bear in mind when conducting tillage operations on a farm.

Cementing Materials. We have seen that as the particles diminish in size, and their total surface increases, there is a marked increase in the cohesion of the mass. The difference in the size of the particles is not, however, the only circumstance which determines the different degrees of cohesion observed in different soils. Soils, in fact, contain various cementing materials, the presence of which has a marked influence on their tenacity. The principal of these cementing materials is clay.

We have already mentioned (p. 16) that ordinary clay consists of extremely fine particles held together by a small proportion of a colloid body. Its constitution thus resembles that of putty, in which the particles of whiting are united by means of linseed oil. In typical clay (kaolin, $Al_2O_3\,2SiO_2\,2H_2O$), derived from the decomposition of felspar, the whole substance has practically the same chemical composition, the various sediments into which it may be divided all containing the same percentages of silica and alumina. The small portion of the clay which possesses a colloid character is probably, however, more hydrated than the rest. The clays ordinarily met with in soil are not, however, chemically homogeneous, the fine sand which they contain commonly consists of quartz particles, though it may at times have a different origin. Thus in marls we have a clay in which the sandy

element is largely composed of calcium carbonate. The true colloid clay is always an aluminium silicate.

The character of a natural clay is largely determined by the size of the particles which form its chief bulk. Hilgard remarks that the groups of coarser particles, numbered 1–9 in Table I, all tend to diminish the tenacity of a soil, while Groups 11–13 increase it. The same amount of true clay will thus generally produce a far more tenacious soil when associated with fine particles than when associated with coarse ones. Curious cases sometimes arise of 'putty soils,' drying to extreme hardness, which contain much coarse sand, while extremely little clay is shown by Hilgard's method of analysis. In such soils there is always sufficient silt to fit in between the coarse particles of sand. We must also bear in mind that the cementing power of clay is confined to the small amount of colloid matter present, and that the proportion of this is not shown by the analysis.

Though the tenacity of heavy soils is largely due to the clay which they contain, it is by no means necessarily in proportion to the amount of clay present. Not only has the fineness or coarseness of the other soil constituents an influence on the cohesion of the mass, the nature of these constituents may also have a considerable effect. The presence of lime and of humus in a clay soil may diminish its tenacity very considerably; ferric oxide, according to Hilgard, also acts in the same direction. For these substances to affect the tenacity of the soil they must be thoroughly distributed throughout it. Aggregations of oxide of iron or of carbonate of calcium occurring in a soil will scarcely affect its general physical texture. We must always remember that the distribution or aggregation of the constituents in a soil is not

shown by a chemical analysis. The physical properties of a soil cannot safely be inferred from its chemical composition. We shall presently have to refer to a variety of other conditions which affect the character of clay soils.

Besides clay, soil contains other colloid bodies which help to bind the particles together. Humic acid is well known as a colloid substance; when combined with lime it possesses considerable cementing power. Schloesing prepares calcium humate by first extracting a soil with dilute hydrochloric acid to remove the bases with which the humic acid is combined, and then, after washing on a filter, extracting with ammonia. To the dark-coloured solution of ammonium humate thus obtained, hydrochloric acid is cautiously added with constant stirring till a precipitate begins to form. A solution of calcium chloride is then added, and the precipitate of calcium humate collected. Schloesing determined the amount of freshly prepared calcium humate required to give a suitable coherence to a siliceous sand, a comparative experiment being made at the same time with a good plastic clay. He found that 1 per cent. of humic acid in the form of calcium humate had as great a cementing power as 11 per cent. of plastic clay. If however the humate is thoroughly dried, and then remoistened, it will be found to have lost its cementing power, while the cementing power of clay remains unaltered by this treatment. Humus is well known as one of the most effective materials for improving the physical condition of sandy soils; it acts partly by giving cohesion to the particles, but still more by increasing the power of the soil to retain water.

We have already mentioned that humus diminishes the tenacity of clay, an action which is plainly the reverse of

that which it exhibits when mixed with sand. The humus of soils is made up of very various matters, consisting as it does of the remains of decayed plant tissue, and of its products in various stages of decomposition. Not only do the coarser parts of the humus tend to lighten a clay with which they are mixed, the colloid products already mentioned act apparently in the same direction. Schloesing mixed with clay 2, 4, and 6 per cent. of calcium humate, and found that with each increase in the proportion of humate the clay became more pulverulent on drying. It is not difficult to conceive possible explanations of this action of humus on clay, but experimental proof is as yet wanting.

Hydrated ferric oxide is another colloid substance which in sandy soils undoubtedly plays the part of a cementing agent. In rocks and soils of the Red Sandstone formations its influence is plainly marked. Perhaps however the most obvious example of the cementing action of ferric oxide is afforded by the formation of iron-pan in moor soils. In moor soils, and especially in those covered by heather, the iron has been dissolved out of the surface soil by the action of the humic acids, the sand at the surface being left remarkably white. The iron passes in solution into the subsoil, where it is reprecipitated, with the result that the sand at a certain depth is cemented together, and an iron-stone produced [1].

[1] The precipitation of the iron oxide may be brought about by contact with calcium carbonate contained in the subsoil; or, possibly, the whole action of solution and precipitation is determined by alterations in the condition of the soil. In autumn and early winter, with a soil saturated with water, the iron may enter into solution as a ferrous salt, and be carried below; and in summer time, in a dry and aërated soil, it may be precipitated as ferric oxide. The iron-pan would then be formed at the line at which oxidation chiefly occurred.

Like humus, the hydrated ferric oxide diminishes the tenacity of clay, while increasing that of sand.

Calcium carbonate is one of the commonest of the cementing materials occurring in rocks. When deposited from its solution in carbonic acid by the escape of this gas, it encrusts and unites the particles on which it is precipitated. This action is familiar to us in the case of petrifying springs.

Calcium carbonate is a common ingredient in soils, and is usually the most abundant of the solid constituents held in solution in soil water. Under the varying conditions of the supply of water and carbonic acid, and with alterations in temperature, calcium carbonate will at times enter into solution in the soil, and at other times be redeposited. By the action of rain and vegetation a gradual removal of carbonate of calcium from the surface soil is generally in progress. In districts in America having a deficient rainfall, a hard pan frequently forms in the subsoil at the depth to which the drainage water usually penetrates; the cementing matter in this pan is carbonate of calcium. The lime-pan, which sometimes forms in English soils which have been dressed with quicklime, is probably due to the conversion into carbonate in the subsoil of the calcium hydrate carried down in the drainage water. The effect of calcium carbonate in increasing the coherence of surface soils is most plainly seen after a dressing of marl or chalk has been applied to a sandy soil. Calcium carbonate is a crystalline and not a colloid body. As already mentioned, it diminishes the tenacity of clay.

Soils usually contain various hydrated silicates, and sometimes hydrated alumina; these colloid substances are doubtless

not without influence on the cohesion of the soil particles, but nothing very definite can be said on the subject.

Coagulation of Clay. The tenacity of a soil containing clay is greatly influenced by the condition of the colloid clay which it contains. If this jelly-like matter is in its fully swelled condition, the soil exhibits its maximum stickiness and is perhaps quite impervious to water; while if this jelly is in a shrunk, coagulated state, the same soil may be pervious to water, and capable of successful tillage.

In the case of a natural soil the facts are complicated by the circumstance that the permeability of a clay soil to water, and the production of a good tilth, largely depend on the formation and maintenance of compound particles, and the conditions under which compound particles are produced are sometimes also favourable to the coagulation of clay. The conditions which destroy compound particles are also sometimes those which bring about the expansion or diffusion of the colloid clay. We may at present state, that a change in the clay from the coagulated to the diffused condition is necessarily destructive to compound particles in all cases in which the colloid clay is an essential constituent of such particles; but the converse is not necessarily true, for it is quite possible to destroy compound particles without affecting the coagulated condition of the clay. The phenomena presented by soils have thus in some cases a mixed origin; in our attempt to understand them we must consider the causes separately.

The behaviour of colloid clay is best studied when we have it diffused in water. Pure clay, when mixed with distilled water, remains permanently suspended in the same, however long the mixture may remain at rest. The addition of

various substances to the water will however speedily bring about the coagulation of the clay, which then completely separates from the water as a flocculent precipitate. If this precipitate is collected, and the precipitating agent separated from it, the clay will be found to have regained its power of permanent suspension in water. This behaviour of colloid clay distinguishes it sharply from the various extremely fine particles with which it is associated, and which are so difficult to separate from it.

If a clay containing fine silt is diffused through water and the clay then coagulated, the whole of the suspended matter falls together, the colloid clay carrying the silt down with it. If the silt is separated, and purified from clay by the methods already described, and is then diffused in water alone, it does not exhibit the phenomena of coagulation when treated with the reagents which precipitate true clay.

The substances which determine the coagulation of clay when diffused in water are very numerous. Acidification with a mineral acid is very effective, and a great number of salts produce this effect. According to Schloesing, who has made a special study of these phenomena (*Chimie agricole*, 62), lime, either as lime water or as salts of calcium, is especially effective, 0·2 gram of lime being sufficient to cause a speedy precipitation in a litre of clay water. Magnesia, according to the same authority, is nearly as effective as lime. The salts of potassium are less effective, and must be used in five times greater quantity than the corresponding calcium salts. The salts of sodium are still less active ; common salt is however a very effective precipitant of clay if used in sufficient quantity.

Sachsse and Becker (*Landwirth. Versuchs-Stationen*, xliii. 15)

state that carbonic acid is an effective precipitant of pure clay. Calcium hydrate they found far more effective than any other calcium salt. Pure clay, when precipitated by lime water, did not apparently carry down lime with it. Monocalcium phosphate was very effective as a precipitant. Sulphate and chloride of ammonium were fair precipitants, as also was chloride of sodium. Nitrate of sodium had very little precipitating power.

Alkaline substances appear generally to favour the diffusion of clay in water, and to destroy flocculation when it has occurred. Ammonia and sodium carbonate possess this property.

The facts now mentioned as to the coagulation of clay have a wide-reaching application. Schloesing points out that the clearness or turbidity of river water depends essentially on the proportion of lime present. For a stream to be capable of depositing the clay brought into it, the water must contain 70–80 mgrams. of lime per litre. Glacier streams are always turbid, owing to the purity of the water. The waters of the Loire and Garonne are turbid, containing respectively 27 and 36 mgrams. of lime per litre. The Rhone clarifies slowly, the lime and magnesia amounting to 68 mgrams. per litre. The Seine clarifies quickly, the lime being 104 mgrams. per litre. The immediate precipitation of river mud on contact with sea water, giving rise to the formation of banks, bars, and deltas, is well known; the principal cause of this precipitation is doubtless the coagulation of the clay on mixing with a strong saline solution.

In soils the same class of facts may be readily observed. In the laboratory, a clay soil may be washed on a filter with weak acid, or with water containing lime, but if distilled water is employed the washings become turbid, and the per-

meability of the soil to water is much diminished. If a treatment with acid has preceded the washing with distilled water, the results just mentioned will be especially apparent. One reason of the accumulation of clay in a subsoil is doubtless the washing out of the clay in the surface soil by rain water.

The amelioration of clay soils by dressings of lime or chalk is a well-known practice; the effect of such dressings is most marked, the clay losing much of its stickiness, becoming more friable, more pervious to water, and being more easily cultivated. A farmer once told the writer that dressing his heavy land with chalk had enabled him to plough with two horses instead of with three as formerly.

Sachsse and Becker filled several wide glass tubes with powdered kaolin and with a powdered heavy loam; some of the tubes were without lime, and some had 2 per cent. of quicklime intimately mixed with the soil. Water was then poured on the surface. Where no lime had been added percolation did not occur, though a considerable head of water lay on the surface. With lime, percolation proceeded regularly in both cases. The kaolin tube without lime burst from the excessive swelling of the clay.

It may be laid down as a general rule that clay soils are friable, and permeable to water, only when the colloid clay is in the coagulated condition.

The action of the various salts used in agriculture upon a clay soil demands much further study. There appears some evidence that salts which determine the coagulation of clay when added to clay diffused in water may nevertheless be capable of disintegrating the particles of a clay soil, and liberating the clay, when used as a strong solution, or allowed to crystallize in the soil. On some heavy soils a top-dressing

of nitrate of sodium produces a marked effect. After heavy rain the water is observed to stand on such soil in puddles, and after the water has disappeared the surface of the soil is seen to be white and glistening. The compound particles of the soil have in fact been disintegrated, a layer of fine sand remains on the surface, and the clay lies under it in a puddled condition. This effect of nitrate of sodium on clay soils results in a sticky condition which greatly increases the difficulty of tillage. The addition of superphosphate to the nitrate would probably do much to prevent this evil, as the lime salts of the superphosphate would tend to preserve the coagulated condition of the clay.

The action of the salts present in the surface soil of alkali-lands is also very marked. The principal salts in the alkali-lands of India and California are sodium sulphate and carbonate; the presence of the latter is particularly harmful. Where the carbonate comes to the surface the wetting of the soil by rain occasions a depression in the land; the clay becomes puddled and impervious to water, and the soil finally dries into sheets of hard pan. This evil admits of cure by treatment with gypsum, which converts the sodium carbonate into the less injurious sodium sulphate. Sodium carbonate has been already mentioned as a salt favouring the diffusion of clay.

Some agriculturists in England speak of the formation of a pan in the subsoil in certain cases in which common salt has been long used as a manure. In the absence of accurate information, it seems probable that these so-called 'salt-pans' had their origin in the washing downwards of fine clay into the subsoil due to the disintegration of the surface particles by the salt.

Frost is an effective agent in bringing about the shrinkage of colloid clay. If water containing colloid clay in suspension is slowly frozen, the water separates as clear ice, and the clay is concentrated in the unfrozen liquid, or finally separated as a solid film. The same action takes place in a soil when it freezes; the drainage waters obtained during a thaw are always remarkable for their brightness.

Shrinkage on Drying. The different constituents of soil behave very differently on drying. It is a well-known fact in the arts that wet sand suffers little change of volume when dried; sand is thus always employed when making moulds for casting metals. The clay used by the potter is equally well known to undergo a considerable contraction on drying; all articles of pottery have therefore to be made considerably larger than the size finally intended.

Schübler carefully determined the amount of contraction suffered by various soil constituents during drying. Cubes made of wet siliceous or calcareous sand did not change in volume on drying. The purest clay available, when treated in the same way, showed a contraction of 18·3 per cent. of its volume; a sandy clay showed a contraction of 6 per cent. The greatest contraction on drying was exhibited by humus, the amount being 20 per cent. of its volume; the humus employed was apparently obtained from the centre of a decayed tree. The various soils he tried varied in their rate of contraction according to the proportions of humus and clay which they contained. An arable soil shrank to the extent of 12 per cent., and a garden soil 14·9 per cent. on drying. From these results we see that contraction on drying is largely determined by the presence of colloid matter in

the soil[1]; that a jelly-like substance should greatly shrink on drying is of course what we should naturally expect.

The facts just mentioned are well known in agriculture. The shrinking and cracking exhibited by clay soils in dry weather, and by moor lands rich in humus, are familiar occurrences. The result of this shrinking of the soil is at first harmful, for the roots of plants are torn, and the cracks in the soil allow of a speedier drying of the subsoil. The after results are, in the case of a clay soil, decidedly beneficial. The fissures established in a time of drought afford in future easy lines of drainage. The texture of the clay is also improved to a considerable depth, the drying and remoistening being favourable to the formation of compound particles. Air is also admitted to the subsoil in exceptional quantity, and oxidation in the subsoil is consequently promoted.

The swelling of dry clay, or of peat, under the influence of rain is also familiar to us. The overflow of peat bogs in an exceptional rainfall has often led to serious results. Hilgard mentions a 'dry bog' soil which increased 30 per cent. in volume when saturated with water. He also mentions that the alkali soils of America, containing sodium carbonate, contract strongly when the powdered soil is wetted. This interesting fact still requires explanation.

Nature and Origin of Tilth. We are now sufficiently acquainted with the constitution and properties of soil to consider the important question of tilth. By tilth we doubtless primarily understand the pulverulent condition of the soil which results from successful tillage. We shall here, however,

[1] Schübler found that precipitated magnesium carbonate lost 15·4 per cent. of its volume on drying. This substance is not usually reckoned as a colloid; it is however exceptionally light and voluminous.

take a general view of the subject, and consider all the various circumstances which serve to bring about this condition.

For land to be in a high degree of fertility it is necessary that the surface soil should exhibit a certain friable, crumbly condition, allowing it to fall into powder on the application of gentle tillage, when containing a medium amount of water. The importance of this favourable texture of soil can hardly be overrated. The success or failure of a crop often depends on the character of the seed-bed at the time of sowing. Not only is a good tilth very favourable to the extension of the delicate roots of the seedling plant; it is also most suitable for ensuring the best conditions of moisture, temperature, and chemical action in the surface soil during the lifetime of the plant, and is thus of the highest importance to fertility. On clay soils the production of a good tilth is especially important; without this there can be no profitable arable culture. The difficulties and delays in attaining this object are the chief obstacle to the effective working of clay land.

Tilth is only partially or indirectly the result of tillage operations. In the case of a stiff soil, tillage frequently does nothing more than place the soil in a condition in which the natural forces producing tilth shall exercise their greatest influence. When tillage directly produces tilth, it is simply due to the fact that the soil has *already acquired* the friable, crumbly condition which is the essential point in the production of tilth. It is important at starting to grasp this fact. A heavy soil is not reduced to powder by mechanical force brought to bear upon it by means of horses and implements; such a task would indeed be far beyond a farmer's

power, and if accomplished would be but a poor imitation of what actually takes place in nature. The favourable texture of soil of which we are speaking may be brought about without any use of implements—it is due to the formation of compound particles in the soil.

In an ordinary fertile surface soil the particles are to a large extent associated in groups; the atoms are, so to speak, built up into molecules; the fine constituents do not behave as separate entities, they form part of larger compound particles. This condition is highly favourable to fertility. In a soil consisting solely of uniform particles, all of one size and substance, the formation of compound particles could not arise, the force of cohesion being in every direction the same. Compound particles also do not arise in soils composed wholly of coarse sand, consisting of particles with a diameter not less than 0·2 mm., the cohesion being in this case too small. Compound particles are produced in soils composed of mixed particles, including a considerable proportion of the finer sizes, and the formation is greatly aided by the presence of colloid constituents capable of acting the part of cement.

A soil may, however, have a constitution very favourable to the formation of compound particles, and yet none may exist; they are formed under some conditions, and destroyed by others. Let us take as an example a good friable loam. If a spadeful of this is taken when very wet, placed on a hearth or paving stone, and thoroughly beaten, we obtain a cake of very stiff mud, utterly unsuitable for the purposes of vegetation, and which will dry into a hard stony mass. By this treatment the compound particles have been shattered and destroyed, and the soil transformed into an aggregation

of ultimate particles, a state in which it exhibits its maximum degree of cohesion.

The action of mechanical force in increasing the plasticity and cohesion of clay is well known to the brickmaker and potter; no clay is used by them till it has gone through the pug-mill, and been ground and beaten in a most thorough manner. If an engineer desires to make clay impervious to water, the same system of mechanical working while it is in a wet state is pursued; the clay is then said to be puddled. The farmer is equally well acquainted with the effects of mechanical force on wet clay. Ploughing a clay soil in wet weather is known to be disastrous to its condition. The effect of very heavy rain on clay land is also to destroy the surface tilth. In all these cases the work done consists in the destruction of compound particles, and the resolution of the clay into a mass of ultimate particles.

Under what conditions are compound particles formed? They arise spontaneously under certain natural conditions. If the lump of beaten loam mentioned above is thrown out upon a garden bed, and left exposed to variable weather for a few months, it will be found completely altered. The lump will be found to have increased considerably in bulk, and, at last, when partially dry, it will fall to pieces when touched. It is now said to have become 'mellow'; the condition of tilth has been re-established; it is now once more a mass of large compound particles having only a moderate adhesion to each other. This change has been brought about by natural agents without the aid of tillage.

The conversion of ultimate into compound particles will not take place in a dry soil, nor in a very wet one. The soil is in the most favourable condition for producing

compound particles when it is rather less than half saturated with water. In this happy condition of moisture there is sufficient freedom of internal movement, without the cohesion of the particles being unduly diminished. When this favourable condition exists, the formation of compound particles is brought about by the alternate expansion and contraction of the mass.

The expansion and contraction of the soil may be simply due to the difference between the day and night temperature, the small alteration in volume being made effectual by its frequent repetition. Much larger changes in volume may, however, be brought about by alternate frost and thaw, and by alternate drying and wetting; and these larger changes produce naturally more speedy results. In freezing, water expands to $\frac{13}{12}$ths of its previous volume, and the expansion of a dry loam after rain will easily exceed this proportion.

In each case in which a moist soil is exposed to the conditions assumed above, we have an unequal expansion and contraction taking place in different parts of the mass. The soil consists of particles of very various size and nature, packed in various ways, coated by films of water of different thickness, and with colloid matter irregularly distributed throughout it. In such a mass, the cohesive force being different in different parts, and the internal strains and pressures also unequal, separations take place along the lines of least resistance, and the mass becomes divided into groups of particles, which as the operation progresses become more and more isolated from each other[1]. During both frost and

[1] It is to be recollected that compound particles are, as already stated, only ormed in soils of *mixed* constitution. Frost will, of course, disintegrate a uniform moist sand, but in such a case no compound particles, but a powder composed of individual grains, will be produced.

drought, a precipitation of the colloid matter must take place on the solid particles of the soil, and tend greatly to increase the stability of existing groups.

The striking effect of winter frosts upon clay land roughly ploughed in autumn is well known to every farmer. The precious tilth thus acquired must be carefully preserved. The following spring cultivation must be done with grubbers and harrows; to plough the land again would be to bury the fine surface soil obtained by winter exposure. When a farmer ploughs heavy land in summer time he has generally to wait till the clods have thoroughly dried, and been again moistened by rain, before he can obtain the required tilth.

These striking changes in the texture of a soil are easily observed, the slower changes are not less important. A perfect cure for an unworkable clay soil is to lay it down to grass. The sod protects the soil from the injurious puddling of the clay by heavy rain. The mischief done by tillage operations ceases. The soil is left to itself, and to the natural influences of the changing seasons. When the land is again ploughed up, it is found that an excellent friable condition of soil has been established.

On old grass land the action of worms in increasing the depth of friable soil is important. The worm-casts consist of soil which has passed through the worm's body; this soil when ejected readily breaks down to a coarse powder. Worms do little to increase the surface soil on arable land, but on grass land the benefits of their action are very considerable.

Specific Gravity. The comparative weights of equal volumes of various soil constituents are shown in the following table.

Table III

SPECIFIC GRAVITY OF SOIL CONSTITUENTS

Water	1.00	Dolomite ...	2.8 – 3.0
Humus ...	1.2 – 1.5	Mica	2.8 – 3.2
Clay	2.50	Hornblende ...	2.9 – 3.4
Quartz	2.62	Augite	3.2 – 3.5
Felspar ...	2.5 – 2.8	Limonite ...	3.4 – 4.0
Talc	2.6 – 2.7	Hematite ...	5.1 – 5.2
Calcite	2.75		

Of all the solid constituents of soil, humus is by much the lightest. Clay is a little lighter than quartz sand, and crystallized calcium carbonate (calcite) a little heavier. These are the most common constituents of soil. Dolomite (calcium and magnesium carbonate) is distinctly heavier than calcite. Of the common siliceous minerals, felspar and talc have specific gravities quite similar to quartz and calcite; mica is distinctly heavier. Hornblende and augite may contain a good deal of iron, and then show a decided increase in specific gravity. Limonite is a natural hydrated ferric oxide; hematite is the same oxide in its anhydrous state. These oxides of iron are the constituents of soil which possess the highest specific gravity. It is clear, from what has been stated, that humus soils will be the lightest, and soils rich in iron the heaviest, if we have regard to their true specific gravity. The true specific gravity of ordinary arable soil is usually about 2·5.

We have already seen that a soil is composed of particles which touch each other only in certain points, spaces filled with water or air lying between them; a cubic foot of dry soil has not therefore the weight which we might assume

from the specific gravity of its constituents, but a weight very much smaller, only a portion of the cubic foot being occupied by solid matter. The weight of a given volume of dry soil, divided by the weight of the same volume of water, is called its 'apparent specific gravity.' According to Wollny, the apparent specific gravity of powdered quartz is 1·449, of clay 1·011, of humus 0·335; all these were weighed in an air-dried condition. As one cubic foot of water weighs 62·32 lb., these specific gravities are equivalent to weights of 90·3 lb., 63·0 lb., and 20·9 lb. per cubic foot. Siliceous sand is thus the heaviest constituent of ordinary soils, clay much lighter, and humus far lighter still. According to Wiley, an ordinary arable soil, in good tilth, will have an apparent specific gravity of about 1·2, and will consequently weigh 74·8 lb. per cubic foot.

The difference between the apparent specific gravities of quartz sand and clay is seen to be considerably greater than the difference in their true specific gravities; this arises from the fact that the extremely fine particles of clay lie more loosely, and are much more difficult to pack than the large heavy particles of sand. The difference between the apparent and true specific gravities is still more marked in the case of humus, the proportion of empty space in dry humus being far greater than it is in the case of either clay or sand.

The whole of the apparent specific gravities and weights per cubic foot given above relate to dry powdered soil, shaken or pressed together in a vessel of known capacity; they represent therefore the weight of soils when in a condition of fine tilth, and not their weight when in a consolidated condition in the field.

King has, by boring, cut out successive cylinders of the

Wisconsin soil to a depth of 6 ft., and determined the weight of dry soil in each foot. One set of determinations will be found in Table IX, p. 70. The first foot of soil, a loam, is seen to weigh 76·8 lb. per cubic foot; while the fifth foot, a fine sand, weighs 116·7 lb. We have here the lighter weight of the loam, and the heavier weight of the sand, both exaggerated by the position in which they occur; the loam being at the surface, and lightened by tillage and vegetation, while the sand is consolidated by the weight of the four feet of soil which lie above it. In a later set of determinations (*Wisconsin 8th Rep.*, 107), the weights vary from 79 lb. per cubic foot for the surface foot of loam, to 111 lb. for the fifth and sixth foot of pure sand. The results furnished by experiments at Rothamsted and Woburn will be found on p. 47.

Anything which tends to diminish the proportion of empty space in a soil, as the presence of stones, or a considerable variety in the size of the particles, leading to closer packing, will tend also to increase the volume weight; while anything tending to loosen the texture of the soil will diminish it.

Weight of Soil per Acre. It is important for many purposes of calculation to be acquainted with the weight of dry soil in a given depth per acre; to ascertain this fact it is necessary to remove definite volumes of the soil, and to dry and weigh them. The accurate information on this head is not very extensive.

The best mode of operation is to drive into the land a short, wide steel tube, sharpened at its lower edge, till the top is level with the surface; the contents of the tube then furnishes a sample of the soil to the depth represented by the length of the tube. The tube should not have a diameter of less than six inches; with narrow tubes, the resistance to the

passage upward of the soil within the tube is so great that the contents of the tube becomes less than that proper to the depth reached. When the sample of the surface soil has been taken in the manner described, the earth can be dug away around the tube, and when the tube has been emptied it can be again driven down, and a sample of the succeeding depth obtained. At Rothamsted, the soil of the experimental fields has been sampled in this way to a depth of nine feet. The iron or steel frame employed at Rothamsted is square in section, the sides of the square being six inches, and the depth nine inches. Table IV shows the average weights of soil per acre obtained at Rothamsted, Herts, and at the experimental farm at Woburn, Beds, by the method just described.

The weights here given represent soils in their natural condition of consolidation. The pasture soil is of course quite undisturbed by tillage, but in the case of the arable soils a part of the upper nine inches has been so disturbed. The Rothamsted soil is a heavy loam, containing many partially rolled flints; it rests on a variable subsoil of loam or clay, beneath which is the chalk. The Woburn soil is a light sand. The stones mentioned in the Table were in every case separated by a sieve having quarter-inch meshes.

Looking first at the total weight of dry soil per acre, we see that the soil is in every case lightest at the surface, and increases gradually in weight as we descend into the subsoil. This is in part due to the increasing pressure to which each succeeding stratum of soil is subjected, and in part to the result of particular actions tending to make the surface soil loose and porous. The action of rain is to wash out of the surface soil its finest particles, and to carry them into the subsoil; the surface soil is thus made up of coarser particles,

Table IV

WEIGHT OF SOIL PER ACRE

1. *Old Pasture, Rothamsted, Loam with Clay Subsoil*

	Original Wet Soil.	Dry Soil.			
		Total.	Stones.	Fine Soil.	Roots.
	lb.	lb.	lb.	lb.	lb.
First 9 inches . .	3,294,380	2,328,973	174,091	2,144,470	10,412
Second 9 inches .	3,867,780	3,098,939	353,322	2,744,715	902
Third 9 inches. .	4,091,620	3,273,324	217,515	3,055,501	308
Fourth 9 inches .	4,139,420	3,343,787	280,730	3,063,057	

2. *Arable Land, Rothamsted, Loam with Clay Subsoil*

First 9 inches . .	3,288,553	2,919,689	340,656	2,578,634	399
Second 9 inches .	3,668,115	3,044,615	141,861	2,902,682	72
Third 9 inches. .	3,882,285	3,215,285	213,190	3,002,095	
Fourth 9 inches .	3,995,723	3,313,563	197,400	3,116,163	

3. *Arable Land, Woburn, Sandy Soil*

First 9 inches . .	3,835,104	3,157,448	93,763	3,063,074	611
Second 9 inches .	3,947,640	3,381,804	201,527	3,180,277	
Third 9 inches. .	4,046,364	3,462,498	170,443	3,292,055	
Fourth 9 inches .	4,014,432	3,501,466	274,239	3,227,227	

with wider interspaces, than the subsoil. In the case of arable land, the mechanical action of rain just described is much aided by the loosening of the surface soil by tillage, and this is itself a direct agent in producing a looser and lighter soil at the surface.

In heavy soils under arable culture, a so-called 'hard pan' or 'clay pan' is often formed immediately under the surface

soil by the treading of horses and men in the furrow, and the pressure of the sole of the plough. The formation of this consolidated layer is clearly aided by the accumulation of fine clay immediately beneath the ploughed soil. Such an impervious layer is of course most injurious to the growth of crops, and if formed requires to be broken up by a subsoil plough following the ordinary plough in the same furrow.

The difference in the weight of the surface soil and subsoil is most marked in the case of the old pasture land at Rothamsted; here the surface nine inches is only three-quarters the weight of the second nine inches. This is an excellent illustration of the lightening of a soil laid down to grass brought about chiefly by the accumulation of vegetable residues in the surface soil.

In cases in which the sampling of the subsoil was carried out at Rothamsted to a greater depth than 36 inches, it appeared that below this depth there was little further increase in the consolidation and weight of the soil.

The sandy soil at Woburn is seen to be, at every depth, of greater weight than the heavy loam at Rothamsted, thus supplying a further illustration of the comparative lightness of clay soils.

The apparent specific gravity, and the weight per cubic foot of the dry soils at the surface, and at the depth of 27 to 36 inches were as follows:—

	Apparent Specific Gravity.	*Weight per Cubic Foot.* lb.
Rothamsted Old Pasture, first 9 inches ...	1·144 ...	71·3
,, ,, ,, fourth ,, ...	1·642 ...	102·3
Rothamsted Arable Land, first 9 inches ...	1·434 ...	89·4
,, ,, ,, fourth ,, ...	1·627 ...	101·4
Woburn Arable Land, first 9 inches ...	1·550 ...	96·6
,, ,, ,, fourth ,, ...	1·715 ...	106·9

These weights supply excellent examples of the consolidation of a soil below the surface.

The distribution of the stones in the Rothamsted soils deserves some attention. Their distribution in the subsoil is extremely irregular in different places, but in the surface soil two points are invariably noticed, namely the deficiency of stones at the surface of the old pasture land, and their marked accumulation at the surface of the arable land. These facts admit of explanation. The sod of a pasture is to a considerable extent a new formation, consisting of living and dead vegetable matter which has been added to and has covered the previous soil. On pastures also the burying action of worms is carried on to its fullest extent, the worm-casts of fine earth, brought from the subsoil, covering the stones and causing them apparently to sink beneath the surface. In the case of arable land the circumstances are quite different.

When a stony piece of land is dug or ploughed in the autumn, and left exposed to the weather, it will be found in spring time covered with stones. During the winter frosts the surface soil has swollen and become disintegrated, the stones have partially protruded, and have been left surrounded by pulverulent matter. When rain comes, the fine soil is washed away from the stones, which are left exposed on the land, often very much to the farmer's astonishment, who not unfrequently asserts his belief that 'stones grow.' The stones thus accumulated on the surface may be buried again at the next ploughing, but the kind of action here noticed, continued for centuries, tends to a gradual removal of the finest particles from the surface soil, and consequently to an increase in the proportion of stones, where these, as at Rothamsted, consist of flint or other minerals little affected

by weather. On the surface soil the full action of wind and rain, and the disintegration by frost are experienced. It is the finer particles which are first removed, both by mechanical and chemical agents, and the large stones thus gradually become a larger proportion of the whole. The Woburn arable land does not show this accumulation of stones at the surface; this land was in fact in pasture at no very distant date.

In the case of soils derived from an underlying soft rock, say an oolitic limestone, the distribution of stones will be the reverse of that experienced at Rothamsted. The stones, in this case, are easily disintegrated by atmospheric influences, and will therefore be fewer and smaller in the surface soil, and will increase in size and number as we proceed downwards.

Colour of Soil. Soil owes its colour chiefly to two constituents—humus, and ferric oxide. Humus alone causes a soil to be grey when dry, but nearly black when wet. Ferric oxide is the colouring matter of all red soils; the tint varies with the condition of the oxide, and in some cases may be brown or yellowish. The admixture of humus of course modifies the colour.

The intensity of the colour is not a certain indication of the proportion of iron or humus present. If the soil consists of large particles, as a coarse sand, a little ferric oxide or humus may strongly affect the colour, owing to the small extent of surface to be coloured; while a soil consisting of fine particles will need a much larger amount of colouring matter to produce the same tint.

The colour of 'blue lias,' and probably of other blue clays, is due to finely divided iron sulphide, FeS_2. When lias is treated with strong hydrochloric acid the pyrites remain as

a heavy black powder, which yields a sublimate of sulphur when dried and heated in a glass tube (*Jour. Chem. Soc.* 1864, 379).

Odour of Soil. According to Berthelot and André (*Compt. rend.*, cxii. 598) the characteristic odour of soil is due to a volatile organic substance, which can be distilled in the presence of water at the temperature of 60° C. The chemical nature of this body has not been satisfactorily ascertained; it is said to belong probably to the aromatic family.

CHAPTER II

RELATIONS OF SOIL TO WATER

Water required by Crops — Deposition of Dew — Hygroscopic Water — Maximum Water Capacity of Soils—Optimum Proportion of Water—Power of retaining Water—Percolation.

To supply water to the plant is one of the proper functions of the soil. A plant is not constructed with a view to its absorbing water by means of its leaves, or indeed by means of any of its above-ground parts; water is only absorbed from dew or rain by these parts when the plant is in a wilted condition. With this limited exception the whole of the water required by a plant is taken up from the soil through the roots. The amount of water supplied by the soil is one of the most important factors in determining the luxuriance of plant growth. It is seldom that there is a sufficient supply of water during the whole time of the growth of a crop. In localities receiving an ample amount of sunshine the supply of water from the soil becomes the circumstance which more than any other determines the quantity of the produce. The large increase of produce which results from artificial irrigation is well known.

Water required by Crops. A large supply of water is

needful from the soil partly because a living plant contains so large a proportion of water—seldom less than three-quarters of its weight; but still more because the passage of water through the plant is one of the most important means of plant nutrition. Evaporation from the surface of a living plant, chiefly from the leaves, takes place energetically whenever the amount of heat received from the sun, or the state of dryness of the atmosphere, admits of water being converted into vapour. The evaporation of water from the leaf surface produces an upward stream of water from the roots, by means of which the solution of plant food held by the soil is carried to the leaves, and the substances which it contains made use of for the production of organic matter. Thus the greater the evaporation, the greater is the transference of plant food from the soil to the plant.

So plain is the connexion between plant evaporation and plant nutrition, that it has been thought probable that a definite relation exists between the quantity of water evaporated and the quantity of organic matter produced. The relation in question appears to be fairly definite so long as certain conditions remain constant, but to vary considerably under a wider range of circumstances. The following table gives the results arrived at by various investigators employing different methods of experiment (Lawes and Gilbert, *Jour. Hort. Soc.* 1850; Hellriegel, *Exp. Station Record*, iv. 532; King, *Rep. Wisconsin Exp. Station*, 1894, 248; Wollny, *Exp. Station Record*, iv. 532).

That the conditions of the experiment have had a considerable influence on the result is evident from a glance at these figures. Barley, for example, has been experimented with by each investigator, and has under various conditions

required 262, 310, 393, and 774 parts of water to produce one part of dry matter.

TABLE V

WATER EVAPORATED BY GROWING PLANTS FOR ONE PART OF DRY MATTER PRODUCED

Results obtained by							
Lawes and Gilbert.		Hellriegel.		King.		Wollny.	
Beans . . .	214	Beans . .	262	Maize . .	272	Maize . .	233
Wheat . .	225	Peas . .	292	Barley . .	393	Millet . .	416
Peas . . .	235	Barley . .	310	Potatoes .	423	Peas .	447
Red Clover .	249	Red Clover	330	Red Clover	453	Sunflower	490
Barley . .	262	Wheat . .	359	Peas . .	477	Buckwheat	646
		Buckwheat	371	Oats .	557	Oats . .	665
		Lupine .	373			Barley . .	774
		Rye . . .	377			Mustard .	843
		Oats . .	402			Rape . .	912

Two circumstances seem especially to influence the relation of water supply to produce—1. The amount of water supplied; 2. Its richness or poverty in plant food. These two circumstances are naturally connected. When the soil contains little water, the solution in the soil is of a comparatively concentrated character. When much rain has fallen, the supply of water in the soil may be ample, but it usually contains very little plant food. The evaporating organs of the plant are constructed so as to act to the greatest advantage under both circumstances. When much water enters the plant, the cells controlling the stomata in the leaves become turgid, and their swelling determines the opening of the stomata as widely as possible, thus increasing the evaporation. When, on the other hand, the supply of water falls short, the cells in question shrink, the stomata are closed, and evaporation is diminished.

Striking illustrations of the sufficiency of a small supply of water under specially favourable conditions are to be found in the case of some of the soils rich in soluble salts which occur in the semi-arid regions of the western States of North America. Good crops of wheat are here grown with an annual rainfall of 13–18 inches, most of which falls in winter time before the growth of the crop has commenced. The water level in the subsoil is 20–30 feet below the surface. Such a supply of water would prove quite inadequate on the soils of the eastern States. The richness of the saline soils of the western States in soluble plant food will be referred to later (p. 215). The presence of much soluble saline matter in the soil is probably in itself a check to the transpiration of water by the plant.

A plant may succeed in reaching perfect maturity with a scanty supply of water, and in this case there will be a relatively large produce for the quantity of water consumed, but a *maximum crop* will not be obtained in this way. A luxuriant growth demands permanent turgidity of the cells, and in an ordinary climate this condition can only be attained by a large supply, and a large evaporation of water. The largest crops can thus only be grown with a luxurious or wasteful consumption of water.

King's experiments at Wisconsin were made in barrels sunk in pits, the surface of the soil in the barrel being on the level of the field. The crop grown in the field was the same as that grown in the barrel, so that the experimental crop was surrounded by a similar growth in the same manner as it would be under ordinary cultivation. The water was supplied through a pipe passing to the bottom of the barrel, and the water level in the barrel was permanently maintained at six

inches above the bottom. The depth of soil in the barrel was 3 ft. 6 in. With this large and permanent supply of water very luxuriant crops were obtained, far exceeding those produced in the surrounding field. With oats and barley a yield of 10,000 lb. of dry matter per acre was obtained; with potatoes 12,000 lb.; with maize over 20,000 lb. The water consumed would average about 24 inches per acre; a quantity of course far exceeding the summer rainfall. Average English crops, yielding about 4,000 lb. of dry matter per acre, will probably evaporate five or six inches of water during their growth.

There is not enough evidence to point out any particular crop as especially wasteful or economical in its consumption of water; the figures in the table however certainly suggest that the cruciferae should be ranked with those requiring most water, and maize with those requiring least. The subject is a promising one for further investigation.

The principal source of soil water lies of course in the rain, hail, and snow precipitated from the atmosphere; the amount of this precipitation in any place, and its distribution through the different seasons of the year, are facts which fundamentally affect the fertility of the land. The amount and distribution of the rainfall is however a subject lying beyond the scope of the present lectures. Of the underground water supply, which in some localities is of very considerable agricultural importance, we shall have something to say by-and-by. It will be convenient before proceeding further to notice two sources of water supply to the soil which are of minor importance, but which fairly come under the physical properties of soil.

Deposition of Dew. If air containing water-vapour is

cooled till it becomes supersaturated it will deposit water on the solid bodies with which it may be in contact. If a cold body is introduced into moist air the temperature of the air may be so reduced on the surface of the body that the air becomes supersaturated, and water condenses upon the cold surface. In any case the deposition of dew is greatly favoured by the presence of dust particles on the solid body. A soil must thus gain water from the air whenever the air is sufficiently moist, and the surface of the soil sufficiently cold to occasion precipitation. It more frequently happens that the deposition of dew or hoar-frost takes place on the herbage occupying the surface rather than on the soil itself. Occasions however do arise in our variable climate in which rather considerable amounts of water are condensed upon the surface of arable soil. These occasions occur most frequently towards the end of winter. The soil is still not far above its minimum temperature when the advancing season brings with it a mild moist wind; under such circumstances a considerable deposition of water may occur on the surface of the cold soil. We obtain evidence of this fact by studying the results furnished by drain-gauges filled with bare soil. In the case of Mr. Greaves' drain-gauge, containing fine gravel, kept free from weeds, the monthly drainage through the soil has exceeded the monthly rainfall twice in December, seven times in January, seven times in February, and three times in March, during fourteen years. As in each of these months some evaporation must have taken place from the gravel, the amount of water condensed from the air must have been considerably greater than the differences between rainfall and drainage would indicate. The gravel having little power of retaining water, and being an excellent conductor of heat, was especially suited to exhibit

the results due to rapid changes of temperature. The same class of results is shown, but much less frequently, by the drain-gauges filled with loam at Rothamsted. The persistent wetness of land in February is doubtless connected with the frequent condensation of moisture upon the cold soil.

Besides the deposition of water upon the surface from the atmosphere, there may be deposition on the surface from vapour rising from the subsoil. This will happen chiefly in the case of well-drained soils, made up of coarse particles, in which a free movement of gases can take place. Movements of the soil air will be determined by variations in its temperature and pressure, but the condensation of water-vapour at the surface will of course only happen when the surface is colder than the subsoil. When this is the case a veritable distillation may occur.

An action of this kind may possibly explain in part the maintenance of the moist condition of the surface soil during a nearly rainless winter, which is observed in the case of the early market-garden lands of Florida. These soils consist of coarse sand, and hold on an average only 3 per cent. of water, yet early vegetables are successfully grown on them without irrigation during the winter months. The water level is 15–20 ft. below the surface (*Soils of Florida, Soils Bull.* 13, p. 9).

Hygroscopic Water. Quite apart from the power of a cold body to condense water from a moist atmosphere is the power which bodies possess in a varying degree of condensing water on their surface even when at the temperature of the atmosphere, and even when the air around them is not saturated with water. Every body in a moist atmosphere has a moist surface, the thickness of the covering film of water depending on the temperature, and on the degree of saturation of the

atmosphere. Such water is known as hygroscopic water. It is parted with slowly in a perfectly dry atmosphere, or on a sufficient rise in temperature.

The amount of hygroscopic water belonging to any given weight of a substance depends on its extent of surface ; a mass of glass becomes far more hygroscopic when reduced to powder. Porous bodies are thus especially hygroscopic. Wood charcoal recently burnt will increase about 20 per cent. in weight in a moist atmosphere.

In comparing the power of different bodies to absorb water-vapour, the question is often complicated by the existence of affinities for water which are quite distinct from the purely surface action we have just described. Water-vapour may be absorbed in large quantities by bodies which have a chemical affinity for water, and form hydrates with it, as in the case of calcium chloride, potassium carbonate, and many other salts. It may also be absorbed to a considerable extent by colloid bodies, as silk or gelatine ; the water in this case is not held simply at the surface, but penetrates the whole mass.

Bemmelen (*Rec. Trav. Chim.*, vii. 37) has made a long investigation on the amount of water held by the dried gelatinous precipitates of silica, ferric oxide, alumina, and other similar colloid bodies, and on the gain or loss of water which they suffer at various temperatures, both in dry and moist air. These precipitates when dried by long exposure to ordinary air contain a large quantity of water. Placed in perfectly dry air (over strong sulphuric acid) a portion of this water is lost [1].

[1] The precipitated ferric oxide used in some of my own experiments still contained 15·5 per cent. of water after drying over sulphuric acid, and precipitated alumina 33·1 per cent.

Heated to 100° C. still more water is lost. Heating to 300° C. fails however to remove the whole of the water, which can only be certainly expelled at a red heat. If these substances have not been over-heated, a considerable part of the water lost is regained when they are placed in a moist atmosphere.

In the case of an ordinary soil of mixed constitution, the power of absorbing water-vapour depends in part on the extent of surface which it presents, that is, on the fineness of its particles; but it depends also to a still greater extent on the amount and character of its colloid constituents. Chemists are at present unable to separate with certainty the portions of water held in these various ways; all we can say is that the water lost in perfectly dry air is that most feebly held, and that the water expelled by heat is more firmly combined in proportion as it requires a higher temperature for its expulsion. We may indeed be certain that water requiring a higher temperature than 100° C. for its expulsion is not hygroscopic water held on the surface of a non-colloid body; but, on the other hand, we may be equally certain that the water expelled below that temperature has been derived in part from the colloids present. It is important to bear in mind that soil dried at 100° C. is not dry, but that the colloids still hold water; any further loss obtained on ignition is thus not simply due to the combustion of organic matter, but is occasioned in part by a further loss of water by the clay and other silicates, and by the colloid ferric oxide and alumina which may be present. Loss on ignition is thus no measure of the amount of organic matter present.

The methods used for determining the hygroscopic water in soils have varied a good deal, and the results obtained

by different investigators are often not comparable. In some methods the powdered soil is dried over sulphuric acid, or at 100° C., and then placed in an atmosphere saturated with water, and the gain in weight determined. Such a method affords low results. In Hilgard's method the air-dried soil is exposed to a saturated atmosphere at about 15° C., weighed, and then dried at 200° C. This method will yield maximum results, more of the colloid water being included.

The following table will give a general idea of the absorptive power of Mississippi and California soils for water-vapour as determined by Hilgard and Loughridge (*Portland Meeting, American Ass. Advanc. Science,* 1873; *Rep. Agri. Expt. Stations California,* 1892–3–4, 70). In the rough classification here adopted, a sandy soil contains less than 5 per cent. of clay; a sandy loam 5–10 per cent.; a loam 10–15 per cent.; a clay loam 15–20 per cent.; and a clay soil over 20 per cent. of clay, as determined by Hilgard's method of mechanical analysis (see p. 12).

TABLE VI

WATER EXPELLED AT 200° C. FROM SOILS SATURATED WITH WATER-VAPOUR, PER 100 OF DRY SOIL (HILGARD)

	Minimum.	Maximum.	Average.
Sandy Soils . .	0·79	4·18	2·59
Sandy Loams . .	1·84	6·12	3·39
Loams	2·30	9·18	5·19
Clay Loams . .	5·06	10·26	6·49
Clays	4·20	18·60	10·83

This rough classification plainly shows that the power of absorbing water-vapour is least in the case of sandy soils;

the coarsest sand was the one absorbing only 0·79 per cent. of water. As the proportion of clay increases the absorptive power for water-vapour rises. In one case the whole soil and some of the separated portions from its mechanical analysis, were individually tested as to their power of absorbing water-vapour; the percentages of water expelled at 200° C. were as follows.

Whole Soil.	*Separated Portions.*			
	Clay.	Hydraulic Value in millimetres per second.		
		< 0.25	0.25	0.50
5.34	17.60	7.96	2.91	1.73

The various fine constituents and colloids classed as clay had thus by far the greatest power of absorbing water, and the coarsest constituents the least.

The connexion between the percentage of true clay in a soil and its absorptive power is not a very close one; clay, in fact, is not the constituent of soil possessing the highest absorptive power; the purest clay experimented with (the pipe-clay of Table I) absorbed in fact only 9·09 per cent. of water. The constituents of soil having the highest absorptive power are humus, ferric oxide, and the hydrated silicates decomposable by acids; if either of these is present in considerable quantity, the soil will have a high absorptive power irrespective of the proportion of clay it may contain. In cultivated soils the hygroscopic power is determined most frequently by the proportion of humus present.

The soils examined by Loughridge having the highest absorptive power for water-vapour were some from the Sandwich Islands; these soils were derived from the decomposition of lava, and were extremely rich in hydrated silicates, in hydrated alumina and ferric oxide, and in some cases humus.

The percentage of water expelled at 200° C. from the vapour-saturated soils amounted in one case to 37·4 per cent. of the weight of the dry soil.

When a substance condenses water from the atmosphere its temperature rises, the water necessarily evolving heat when passing from the gaseous to the liquid state. Stellwaag (Wollny, *Forsch. der Agrikulturphysik*, v. 210) determined the rise in temperature of various soil constituents, first dried at 105° C. and then placed in a saturated atmosphere at 30° C. The changes in temperature observed give an excellent idea of the relative hygroscopic power of the materials experimented with.

Rise in Temperature in Water-vapour at 30°

Quartz Sand	0°.88 C.
Calcium Carbonate (precipitated) ...	1°.47
Kaolin	2°.63
Hydrated Ferric Oxide	9°.30
Peat	12°.25

The moistening of a dry body with liquid water, and especially the combination of a colloid body with water, also produces a rise in temperature. At 10° C. the results obtained were as follows.

Rise in Temperature when moistened with Liquid Water

Quartz Sand	0°.10 C.
Calcium Carbonate (precipitated) ...	0°.28
Kaolin	0°.83
Hydrated Ferric Oxide	6°.60

Sachs has taught, and his statement is current in modern textbooks, that plants are able to make use of the hygroscopic water in soils; and that, in fact, a supply of water-vapour in the air is sufficient to preserve such an amount of water in the

soil as will maintain the plant cells in a turgid condition. It is of course possible that if changes of temperature are allowed, the amount of water condensed by the soil may suffice for the maintenance of a plant; but it is not true that a soil containing only hygroscopic water is capable of maintaining plant life, and this has been abundantly proved by the investigations of Heinrich, A. Mayer, Liebenberg, and Hellriegel (*Jahresb. Agrik. Chem.* 1875–6, 368).

Heinrich grew plants in very small boxes till fully developed, and then placed them under conditions of very little evaporation till they began to wilt; the soil in the box was then mixed, and the proportion of water it contained determined. A variety of soils were employed. A weighed quantity of each soil was also placed in a dry state in a saturated atmosphere till it ceased to gain weight, and the amount of hygroscopic water which the soil could absorb was thus determined[1]. It was found in every experiment, that when the plants wilted the percentage of water in the soil was still somewhat higher than that proper to hygroscopic water only. The figures given in Table VII show the average results obtained with oats and maize.

Experiments made with grasses, with various leguminosae, and with potatoes, gave similar results. The potatoes grown in peat required 41·4 per cent. of water in the moist peat, or 70·8 per 100 of dry peat, to avoid wilting[2]. The leguminous

[1] The hygroscopic water found would have been higher had the soils been dried at 200° C., but this fact will not alter the conclusion drawn from the experiment, as the amount of water remaining in the soil after the growth of the plant would in that case have also to be determined at 200° C.

[2] In experiments on the growth of crops on peaty land it has been noticed that the peat must contain more than 60 per cent. its weight of water to yield productive crops (*Biedermann's Central-Blatt für Agrikulturchemie*, 1885, 297).

plants required slightly more water than the grasses and cereals.

TABLE VII

RELATION OF PLANTS TO HYGROSCOPIC WATER (HEINRICH)

	Water per 100 of Dry Soil.	
	When Plants wilted.	Absorbed from Moist Air.
Coarse Sandy Soil	1.5	1.15
Sandy Garden Soil	4.6	3.00
Fine Humus Sand	6.2	3.98
Sandy Loam	7.8	5.74
Calcareous Soil	9.8	5.20
Peat	49.7	42.30

From what has now been said it seems clear that if we desire to know how much water available for plant use a soil contains, we shall arrive at the result best by ascertaining how much water the soil loses when exposed to ordinary air till it ceases to lose weight. Water which can only be expelled by heat is incapable of assimilation by ordinary crops.

Although a soil containing only hygroscopic water cannot support a crop, the possession of hygroscopic power is under some conditions of distinct advantage to a soil. Hilgard has observed that in the arid districts of California it is only on soils capable of absorbing 4–8 per cent. of hygroscopic water that crops can successfully resist drought. He thinks that the surface soil is cooled during the extreme heat of the day by the evaporation of a portion of the hygroscopic water, this water being regained during the night either from the atmosphere, or from the vapour rising from the subsoil.

Water Capacity of Soils. A soil contains the largest pos-

sible quantity of water when all the interspaces between the particles are filled by that liquid, the soil is then perfectly saturated. The quantity of water which a soil may contain when in a saturated condition is thus determined by the volume of its interspaces. The circumstances which determine the proportion of interspaces in a soil have been already mentioned (p. 1), and should be referred to once more before pursuing the subject any further; the experimental results we are about to describe will serve to illustrate the principles there laid down.

The proportion of interspaces in any volume of soil may be ascertained by determining the quantity of water which it holds when perfectly saturated. It may also be ascertained by calculation, if both the apparent specific gravity of the dry soil and the real specific gravity of its mixed constituents are known. Thus, if we deduct the weight of 1 litre of the dry soil from the weight of 1 litre of the solid soil constituents, and divide the difference by the specific gravity of the soil constituents, we obtain the volume of the interstices in 1 litre expressed in terms of water.

Numerous determinations in natural gravel and sand of various degrees of fineness, and in artificial mineral powders, show that so long as the material itself is non-porous, the interstices are generally about 40 per cent. of the whole volume. The volume of the interstices tends to rise when the particles are very small, owing to the looser packing under these conditions; it tends also to rise when the particles are of uniform dimensions. It falls when the variation in size is considerable, owing to the closer packing which then takes place from the insertion of small particles in the spaces between larger ones.

Flügge's experiments with gravel, sand, and a mixture of equal parts of both, furnish a good illustration of the very similar results obtained with masses composed of very different sized particles, and of the diminution in the volume of the interstices when large and small particles are mixed.

Volume of Interstices per cent. of Total Volume

Gravel	38.4 – 40.1
Sand	35.6 – 40.8
Gravel and Sand ...	23.1 – 28.9

In ordinary soils, the volume of the interstices will generally be somewhat greater than in the case of sand or gravel; this is owing to the presence of porous or compound particles in the soil. Particles of chalk or limestone are porous; particles of humus are highly porous. Compound particles occur abundantly, as we have already seen, in all soils in a condition of good tilth. As the proportion of porous particles in the soil increases, so also will its capacity for containing water.

A soil abounding in porous or compound particles has its capacity for water diminished if the soil is reduced to a fine powder in the laboratory. Zenger found that the soil from a peaty meadow, 100 parts by weight of which were capable of holding 178 parts of water, had its capacity for water reduced to 103 when finely powdered.

There is one factor which influences the water capacity of soil, which, however, has no relation to the volume of the interspaces; this is the action of the colloid constituents. Colloid bodies placed in contact with water take up a considerable quantity, and swell considerably. We have already noticed (p. 35) the increase in volume in peat and clay which

takes place when they are wetted. When soils swell on being wetted, it is obvious that the quantity of water they will hold when saturated must be in excess of that calculated from their interstices when dry. Hilgard and Loughridge regard the hydrated silicates in the California soils as having a distinct influence on their capacity for holding water.

In ordinary soils, humus is the constituent which most powerfully influences the water-holding capacity. It acts in a double way; first, by increasing the volume of the interspaces through its great porosity; and second, by its absorption of water due to the colloid nature of some of its constituents.

As examples of the proportion of water held by various soils when fully saturated we may quote the results obtained by Meister (*Jahresb. Agrik. Chem.* 1859–60, 36), by Schwarz, and by Hilgard and Loughridge.

TABLE VIII

WATER IN FULLY SATURATED SOILS (MEISTER)

	Volume of Water per 100 Volumes of Soil.	Water by Weight.	
		In 100 Wet Soil.	Per 100 Dry Soil.
Sandy Soil . .	45·4	23·3	30·4
Chalk Soil . .	49·5	28·2	39·2
Clay	50·0	27·8	38·5
Loam	60·1	31·2	45·4
Garden Earth .	69·0	43·4	76·8

WATER IN FULLY SATURATED SOILS (SCHWARZ)

Coarse Sand . .	39·4	19·8	24·7
Loam	45·1	24·3	32·2
Clay	52·7	30·8	44·5
Peat Subsoil . .	84·0	78·2	359·0

Looking first at the volume of water in a given volume of soil, we see in each case that the proportion is lowest in a sandy soil, rises somewhat when the soil is calcareous, or is a loam or clay, and reaches its highest point when humus is present. The figure obtained by Schwarz for peat is doubtless below the truth; as his figures were obtained by calculation from specific gravities, the result of the swelling of the peat on wetting is thus excluded.

Hilgard and Loughridge (*Rep. Agri. Exp. Stat. California*, 1892–3–4, 80) found that the California soils were usually saturated by 44–60 per cent. their volume of water; a very coarse sand was saturated with 37·5 per cent. its volume. The soils which distinctly swelled or shrank when wetted are excluded from this statement, as their final volume was not accurately known. The proportion by weight varied from 23–68 of water per 100 of air-dried soil.

Hilgard's method for determining the water capacity of a soil is to use a circular brass box having a sieve bottom, 10 mm. in depth, and having a capacity of 25 cc.; the weight of the box is known. This box is filled with the air-dried soil in powder, the soil settled by tapping the box on the table, the surface struck level with a thread of silk, and the box then weighed. The box is then supported on a triangle in water, so that the bottom of the box is just beneath the surface of the water. The box is left thus for an hour or more, till the soil is fully saturated; the box is then rapidly wiped and weighed. The result can be calculated both by volume and weight.

In analyses of soil the proportions of water, and other constituents, are usually stated by weight; this mode of statement may, however, lead to a serious misinterpretation of the

results when soils of different volume weights are compared. It is the quantity of plant food in a given *volume* of soil which determines its poverty or richness. The roots are distributed through a certain space : it is the quantity of water and of plant food in that space which is important. We have already seen (pp. 42 and 47) that the volume weights, or apparent specific gravities of different soils may vary greatly, the extreme differences being shown by sand and humus. In Table VIII the proportion of water has been calculated both in respect of the volume and of the weight of the soil; the results by weight are also expressed both as percentages of the wet soil, which is the usual English mode, and also as per hundred of dry soil, which is a mode frequently adopted by American and foreign writers. It will be seen at once that the relative value of the different soils as storehouses of water for the plant appears wholly different according to the particular mode of statement we regard. Thus, reckoned by volume, the peat subsoil is seen to supply rather more than twice as much water as the coarse sand, and this is the relation between them perceived by a plant. If, however, we look at the percentage by weight reckoned on the wet soil, we should conclude that the peat supplied four times as much water as the sand; and looking at the figures per 100 dry soil, we should conclude that it supplied fifteen times as much water as the sand. The unfairness of these comparisons by weight is at once apparent if we recollect that in the last case we are really comparing the water in seven volumes of wet peat with the water in one volume of wet sand.

Experiments were made by King (*Wisconsin 6th Rep.*, 196) on the amount of water required to saturate the soil and subsoil of his station when these were in their *natural con-*

dition of consolidation. Metal cylinders, one foot in depth and six inches in diameter, were driven into the soil to their upper edge, and then removed full of soil for experiment. Successive cylinders were thus filled down to five feet from the surface. The five cylinders were then placed in a tank of water till completely saturated. They were weighed in two conditions: (1) immediately after leaving the water; (2) after draining four days in a saturated atmosphere. The results were as shown in Table IX.

TABLE IX

WATER IN SATURATED WISCONSIN SOILS (KING)

	Weight of Dry Soil per Cubic Foot.	Fully Saturated.		Drained Four Days.	
		Water per 100 Dry Soil.	Water Inches.	Water per 100 Dry Soil.	Water Inches.
	lb.				
1. Marly Loam .	76.8	41.3	5.88	32.2	4.59
2. Reddish Clay .	96.4	28.1	5.03	23.8	4.26
3. Reddish Clay .	96.2	28.4	5.07	24.5	4.37
4. Sandy Clay . .	101.5	24.8	4.67	22.6	4.25
5. Fine Sand . .	116.7	17.4	3.76	17.5	3.77
In five feet . .			24.41		21.24

These results are interesting in several ways. They illustrate the different capacity for water of sand and clay, which is shown in an exaggerated manner by the percentage by weight, and truthfully by the number of inches of water per unit of area. They show also the maximum amount of water which might be contained in five feet of soil[1].

[1] If the dry weight of a cubic foot of natural soil is known, and the specific gravity of the soil is accurately ascertained, it is easy to calculate the proportion of interstices in 100 volumes of the soil, and consequently the

The quantities of water, ascertained by a laboratory experiment, as capable of being held by any soil are but seldom realized under natural conditions in the field. It is indeed a difficult task thoroughly to saturate a soil with water. The interstices of a dry soil are full of air, and unless the whole of this air is allowed to escape the soil cannot become fully saturated. In the laboratory saturation is best effected by allowing the water to rise into the soil from beneath; the air then easily escapes through the dry soil above. In nature this proceeding is reversed, the rain falling on the surface and hindering the escape of air. It is thus only after long continued rain that soils are found in a fully saturated condition. Illustrations of the amounts of water held by field soils in their wettest condition will be found in Table X. Nos. 1–5 are Wisconsin soils, examined by King thirty-two hours after a rainfall of over three inches (*Wisconsin 7th Rep.*, 152). Nos. 6–8 are soils from Broadbalk wheat field, Rothamsted, examined by Lawes and Gilbert (*J. Roy. Agri. Soc.* 1871, 110).

These figures are on the whole somewhat lower than the percentages by weight given in Table IX as the result of laboratory experiments.

maximum amount of water it is capable of holding. This mode of work will lead to more accurate results than experiments made in the laboratory on powdered soils, not only because the soil is taken in its natural state of consolidation, but also because, if the cubic foot is measured in a moist condition, the considerable errors which sometimes arise from the change in volume of the soil on wetting are entirely avoided. If a cubic foot of moist sand weighs when perfectly dry 110 lb., and the sand has a specific gravity of 2·62, then the sand contains 32·6 per cent. of its volume of interspaces, and would hold when saturated that proportion of water. On the other hand, a cubic foot of clay, weighing when dry 75 lb., and of a specific gravity 2·50, will contain 51·9 per cent. its volume of interspaces. These are nearly extreme cases; ordinary soils (peat of course excluded) will fall between these limits.

TABLE X

WATER IN NATURALLY SATURATED SOILS

	Weight of Water	
	Per 100 Wet Soil.	Per 100 Dry Soil.
1. Quartz Sand (at water level)	18·4	22·5
2. Clay Loam	22·4	28·9
3. Ditto	24·9	33·2
4. Brick Clay	24·1	31·8
5. Black Marsh	25·7	34·7
6. Loam, unmanured 26 years	23·0	29·9
7. Loam, artificial manure 26 years	24·7	32·8
8. Loam, farmyard manure 26 years . . .	37·6	60·2

The Broadbalk soils afford a good illustration of the influence of manures on the water capacity of a soil. These soils had grown wheat continuously for twenty-five years; they were sampled in January 1869 after long continued rain. The figures show the quantities of water held in the first six inches of soil. The soil which had been continuously unmanured holds the least water. The soil which had grown large crops of wheat with artificial manures holds distinctly more water: here the soil contains more humus, the residue of the roots and stubble of the larger wheat crop. The soil which had received 14 tons of farmyard manure annually for twenty-six years far exceeds all the others in the amount of water which it contains, owing to the large accumulations of humic matter within it. The accumulation of humus, and the increased water-holding power associated with it, is however practically limited to the first nine inches from the surface.

Illustrations of the amount of water held by a field soil in a natural state of consolidation, and in its wettest condition, are furnished both by the Rothamsted and Wisconsin ex-

periments. Water was determined in the Broadbalk soils down to 3 ft. below the surface in January 1869; the highest mean percentage of water found was 26·71, the lowest 23·17. Taking the weight of dry fine soil down to 3 ft. as 11·6 million lb. per acre (see Table IV), the water contents to that depth become respectively 18·68 and 15·47 inches per acre. In the case of the Wisconsin soils, in a natural state of consolidation, but saturated in the laboratory (Table IX), the upper three feet of soil contained 15·98 inches when fully saturated, and 13·12 inches after draining for four days. Both the soils may be generally described as clay loams.

The quantities of water per acre just mentioned, supplemented by the summer rainfall, would be fully equal to the demands of the largest crop that could be grown (p. 55). The quantity of water contained in a soil saturated by rain is not, however, permanently held, but rapidly diminishes by percolation and evaporation. The diminution of the quantity of water in the soil below the point of saturation is indeed essential for healthy plant growth.

Optimum Proportion of Water. When a soil is fully saturated with water air is of course entirely excluded; this condition is most injurious to the health of plants. Many plants may indeed be grown with their roots immersed in water, if this water is freely exposed to air; but the water in a subsoil is exposed to air only when the interstices of the soil are but partly occupied with water. Experiments have been made by Hellriegel, and by Wollny, in which agricultural plants were grown in jars of soil in which certain proportions of water were constantly maintained. It appeared that when the soil contained 80 per cent. of the water required to saturate it, the proportion was too high, and that when the water amounted

to only 30 per cent. of the saturation quantity, the proportion was too low for the production of a maximum crop. The largest crops were obtained when the proportion of water lay between 40 and 60 per cent. of that required for full saturation. When a soil is half saturated with water it of course implies that the interspaces are half filled with air, and this is apparently the condition to be aimed at.

Power of Retaining Water. The utmost capacity of a soil for water is a subject of comparatively little practical importance, as most soils are fully saturated only when the level of standing water is quite near the surface, or immediately after long continued heavy rain. Soils usually occur in nature in a more or less drained condition, and it is the quantity of water which they retain when fully drained which determines the supply which they are able to furnish to a crop. The proportion of water held by a soil in a fully drained condition is termed by Mayer its absolute water capacity.

If a wide tube of sufficient length is filled with coarse sand, consisting of particles of uniform size, the lower end of the tube being closed by a piece of linen, and water then poured on the top of the sand till it is fully saturated, and the whole then allowed to stand till dropping ceases, there will be found in the tube two distinct layers of wet sand, a short column at the bottom fully saturated, and a long column above it fully drained, and containing throughout a nearly uniform proportion of water. In the lower layer the interstices are completely filled with water. In the upper layer the water coats the surfaces of the particles, and is held around their points of contact, but the main interspaces are empty.

If the particles of the sand are not uniform in size, but consist of a mixture of large and small, as in a natural soil,

then, when dropping has ceased, three layers may be distinguished, but the divisions are not marked with the sharpness that appeared in the former case. The lowest layer as before is fully saturated, and the highest layer is fully drained, and contains a uniform proportion of water, but there lies between them an intermediate layer, often of considerable length, in which the proportion of water is not uniform but increases from above downwards till it merges into the full water contents of the lowest layer. In this case, the water in the fully drained layer not only coats the particles, but fills the finest of the interspaces. In the intermediate layer, more and more of the interspaces are occupied with water as the sand gets nearer the bottom, till at last the largest are occupied, and the sand is found completely saturated.

If, in a third case, the tube is filled with an extremely fine powder, firmly packed together, and then saturated with water, this powder may be found to exhibit no loss by drainage, but the tube remains filled throughout with matter of one uniform degree of wetness. In this case the interspaces are so fine that the water filling them is held too firmly to obey the force of gravity. The cause of these various results will be better understood when we have discussed the subject of capillary action.

Schübler made many experiments on the power of various soils to retain water, but his results, and those of other early investigators, are generally too high, the experiments being made in short tubes or funnels in which the soils were never thoroughly drained. A. Mayer has made use of a tube 1 metre long, composed of two pieces joined by caoutchouc, the upper piece 25 cm., the lower 75 cm. in length. The tube is filled with powdered soil, which is then saturated with water. When

drainage has ceased, the upper portion of the tube is disconnected, and the amount of water held by the drained soil which it contains is then determined. Wollny's apparatus follows the same principle, and is still more complete (*Forschungen der Agrikulturphysik*, 1885, 177). It is only by methods such as these that the true amount of water retained by a soil can be ascertained.

We have previously pointed out that the coarseness or fineness of the particles has no direct influence on the quantity of water that will be held by a mass when fully saturated; when however we have to deal with the amount of water retained after thorough draining, the size of the particles, or—to speak more accurately—their extent of surface, becomes the factor having the preponderating influence on the result. The larger are the particles, or the less the internal surface of the mass, the smaller will be the proportion of water retained after draining.

Mayer separated powdered quartz by sifting into three degrees of fineness: when fully saturated, each of these powders contained more than 40 per cent. of its volume of water; when thoroughly drained they retained as follows:—

Diameter of Quartz Particles.	*Volume of Water retained per cent. of Total Volume.*
0·9 – 2·7 mm.	7·0
0·3 – 0·9 mm.	13·7
below 0·3 mm.	44·6

The coarsest powder has thus lost by draining about five-sixths of its water, while the finest powder retains after draining about the same quantity of water which it held when fully saturated. Schloesing points out that the very different relation of fine and coarse particles to water may be shown by sifting a sample of moist sand, and then determining the

proportion of water in the coarser and finer parts; the portion passing through the sieve will be found to contain much the most water.

An excellent illustration of the manner in which water is distributed in columns of sand after thorough draining is afforded by an experiment made by King (*Wisconsin 10th Report*, 176). He filled five tubes, 10 ft. long and 6 inches in diameter, with sand of different degrees of fineness, prepared by sifting successively through sieves having 100, 80, 60, 40 and 20 meshes to the inch. The columns of sand were saturated with water, and then allowed to drain, protected from evaporation, for 111 days; the water in each six inches of every column was then determined. The results given by three of the columns are shown in Table XI.

TABLE XI

WEIGHT OF WATER PER 100 OF DRY SAND AFTER DRAINING 111 DAYS (KING)

	Meshes per inch of Sieves used to prepare Sands.		
	20 – 40	60 – 80	100 – x
	per cent.	per cent.	per cent.
First Foot . . .	1·92	2·40	3·35
Second „ . . .	2·34	2·72	3·53
Third „ . . .	2·36	2·79	4·03
Fourth „ . . .	2·36	2·93	5·16
Fifth „ . . .	2·45	2·98	6·99
Sixth „ . . .	2·62	3·12	9·87
Seventh „ . . .	2·74	3·11	10·98
Eighth „ . . .	3·04	3·54	15·88
Ninth „ . . .	3·81	13·50	18·90
Tenth „ . . .	14·04	20·51	19·99
Mean . . .	3·77	5·76	9·87

We at once see that the finer the sand, the larger is the proportion of water retained after draining. In the case of the two coarser sands it is evident that we nearly approach the condition of a column composed of uniform particles, the proportion of water retained throughout each column varying very little till the bottom is approached. The finest sand is, on the contrary, clearly a mixture of particles of different size, as it is only in the first two feet that we find a uniform minimum contents; from this point downwards the proportion of water rapidly increases.

We have already stated that the reason why a mass of fine particles retains more water after draining than a mass of coarse particles is simply due to the far greater surface for holding water existing in the first instance, and to the much narrower interspaces between the particles. It follows of course that *porous* particles will have a much greater power of retaining water than solid particles of the same dimensions. Mayer prepared a fine powder from quartz, calcspar, claystone, and wood; the particles were in each case as far as possible of the same size (0·3–0·9 mm. diam.). He then determined the volume of water retained by 100 volumes of each powder after draining. The results were as follows:—

Calcspar.	*Quartz.*	*Claystone.*	*Wood.*
11·7 ...	13·7 ...	24·5 ...	45·6

The porous particles thus retained far more water than the solid particles, though all were of approximately the same diameter.

Schloesing has given some determinations of the weight of water held by fully drained soils. His results were as follows:—

Weight of Water in 100 *Drained Soil*

Coarse Sand	... ...	3.0
Fine Sand	... ...	7.3
Calcareous Sand	...	32.0
Clay Soil	... ...	35.0
Forest Soil	... ...	42.0

We have here again examples of the increase of the water-holding power as the particles become finer, or more porous (e. g. calcareous sand). The forest soil consisted chiefly of extremely fine sand, probably with some humus. Some further illustrations of the amount of water held by drained soils will be found in the next section.

The state of consolidation of the soil, or in other words the closeness of the packing of its particles, has a great influence upon its power of retaining water. The operations of tillage may thus supply a means of ameliorating the excessive dryness or wetness of a soil. Referring once more to the examples of the loose and tight packing of soil particles already given on p. 1, it will be evident that in the system of close packing the points of contact between the particles are about twice as numerous as in the system of loose packing (Fig. 1), and the interstitial spaces are also much reduced in size. The closely packed particles will in fact retain when drained at least twice as much water per unit of volume as the loosely packed particles. The reason of this will become clearer when we have discussed the subject of capillary action. In practice, the water-holding power of a coarse sandy soil may be increased by consolidation with a heavy roller, or by the treading of animals on the land. On the other hand the water-holding power of a heavy soil may be greatly reduced if the soil can be pulverized, and brought into a loose state of aggregation.

The amount of water retained by a soil after rain is one of the factors which, more than any other, determines its suitability for different kinds of agricultural crops. The typical American soils described on p. 20 owe their suitability for their respective cultures chiefly to the varying percentages of water which they retain. The requirements of a plant for water vary a good deal in the various stages of its life. In the earlier stage of leafy growth, when the production of vegetable tissue is proceeding with the greatest vigour, the demand for water is greatest, and luxuriant growth at this period is largely determined by the quantity of water supplied. But in the later stage of seed production, when the transference of matter rather than its new formation is the great business of the plant, the presence of an excess of water is for many plants highly injurious, and greatly diminishes the proportion of seed yielded by the plant. For seed production, therefore, dry conditions are desirable.

The general idea of the relation of water supply to plant function we have just presented serves to explain why different crops, or different styles of culture, require different proportions of water in the soil. Wheat land must be drier than grass land, if both crops are to develop to the best advantage. A soil for the production of a fine sample of malting barley must be drier than one yielding maximum wheat crops. A soil that is to supply early market-garden crops must be a dry one, for the object is to obtain early and not heavy crops; and to obtain early maturity the crop must be hastened through its preliminary stage of tissue formation and brought as quickly as possible to the completion of its career.

Little information exists as to the proportion of water actually held by the soils most suitable for the production

of various crops; a commencement of an investigation of this kind has however been made in America. Certain typical soils in various places have been left for the purpose of experiment without a crop, and samples of the soil have been obtained every day by boring to the depth of 1 ft., and in these samples the proportion of water has been determined. Whitney (*Soils, Bulletin* 3) gives the results of the mechanical analysis of these soils, and also the amounts of water which they contained in the months of June and July 1895.

TABLE XII

PHYSICAL ANALYSIS OF TYPICAL SOILS (WHITNEY)

Diameter of Particles.	mm.	Market-garden Soil.	Bright Tobacco Soil.	Shipping Tobacco Soil.	Burley Tobacco and Grass Soil.
Fine Gravel	1·0 – 2·0	0·06	0·71	0·05	1·76
Coarse Sand	0·5 – 1·0	0·46	1·12	0·18	1·63
Medium Sand	0·25 – 0·50	7·08	7·37	0·11	1·24
Fine Sand	0·10 – 0·25	48·43	27·90	0·34	0·58
Very Fine Sand	0·05 – 0·10	26·20	24·26	5·13	1·59
Silt	0·01 – 0·05	8·52	22·77	63·28	46·36
Fine Silt	0·005 – 0·01	3·20	4·20	5·19	9·56
Clay	...	4·55	8·30	20·55	30·20
Loss at 100°		0·15	2·07	2·10	4·29
Loss on ignition		1·10	0·15	3·06	5·32
Total		99·75	98·85	99·99	102·53

Percentage of Water in 1 ft. of Soil, June and July 1895

	Market-garden Soil.	Bright Tobacco Soil.	Shipping Tobacco Soil.	Burley Tobacco and Grass Soil.
	per cent.	per cent.	per cent.	per cent.
Minimum	6·2	4·0	12·1	18·0
Maximum	10·5	11·7	17·9	23·1
Average	8·7	7·2	15·1	20·1

These soils were in different localities; the results do not therefore show how different soils behave with the same rainfall, but rather the amount of water found in soils specially suited to certain crops in a season of fair average production. The soils best suited for market-garden purposes, or for the growth of the bright yellow tobacco used for cigarettes, thus only held from 5–11 per cent. of water; the shipping tobacco soil 12–18 per cent.; and the pasture soil (used also for the coarsest tobacco) 18–23 per cent. Each of these conditions was especially suited for the purpose of the particular crop cultivated.

A detailed account of the physical texture and water-holding power of soils producing distinct varieties of tobacco is given by Whitney in a later Bulletin (*Soils, No.* 11). The delicate, elastic leaf, used for cigar wrappers, and the bright yellow tobacco already referred to, are only produced on sandy soils holding but little water. The thicker, coarser leaf, with which is associated a much larger return per acre, is grown on soils containing a more or less considerable proportion of clay, and holding a much larger quantity of water.

According to Whitney's observations, the water contents may rise to one-quarter more than the normal amount, or fall to one-quarter below it, without seriously disturbing the characteristic quality of the soil. With a greater diminution of water drought will be felt, and with a permanently greater increase in the water contents the crop will be injured.

An attempt is being made in the United States to obtain daily records of the water contents of typical soils by measuring the resistance to an electric current passing between two electrodes sunk in the soil.

Before leaving this section we may sum up the chief conclusions by saying that extreme fineness of the particles is by itself capable of giving to a soil a maximum power of retaining water, this condition alone sufficing to keep all interstices full of water after percolation has ceased. The quantity of water retained is thus in proportion to the internal surface, and is doubtless increased by the presence of colloid bodies in the soil. Of all soils peat has the greatest capacity for retaining water, its porosity supplying an enormous internal surface, the effect of which is heightened by the affinity for water of its colloid constituents. At the other end of the scale we have gravels and coarse sands, which have hardly any power of retaining water. For swamp-loving crops, as rice, soils retaining a maximum amount of water are desirable; soils having a high retentive power may also have a special value in climates of small rainfall. For ordinary farm crops it has been already pointed out that a very large proportion of water in the soil is distinctly injurious, and that the most vigorous growth is obtained when the soil contains about one-half of its saturation quantity.

Sandy soils are by no means so inferior as suppliers of water as is often supposed. We must recollect that the quantity of water retained by a given volume of sand is greater than would appear from the usual percentage determinations made by weight. A moist sand containing 7 per cent. of water by weight, contains 11·2 vols. of water per 100 vols.; and this difference between weight and volume is greater in the case of sand than in the case of a clay soil, and still more than in the case of a soil containing humus, owing to the higher weight per cubic foot of the sand. The soils just named are in fact not so unequal when their

water contents is expressed in pounds per cubic foot as when it is expressed as per cents. by weight.

We have further to bear in mind the fact already noticed (Table VII), that a sand gives up its water far more completely to a crop than will clay or humus. This is in great measure due to the smaller internal surface of the sandy soil. In the case of a sandy and clay soil, both containing 7 per cent. of water, the water in the sand occurs as a much thicker film, being spread over a much smaller surface; it is thus in a condition better suited for absorption by the roots of plants. The same weight of water in the clay soil is held as an extremely thin film, being spread over an enormous surface. The thinner is the water film the more firmly is it held by the solid particles of the soil, till it finally becomes quite incapable of assimilation by plants. The greater availability of the water in a sandy soil will also be partly due to the absence of the colloid bodies which occur in clay and humus, as these, as we have already seen, have the property of firmly retaining water.

We have further to take into account the wider distribution of the roots in a sandy soil, and the greater freedom with which water moves within it.

The facts just mentioned will not unfrequently turn the balance in favour of a sandy soil as a supplier of water to the crop. King (*The Soil*, 161) mentions the case of a sandy and clay soil at Wisconsin having water capacities of 18 and 26 per cent. Maize grown on these soils reduced the water in the sand to 4·17, and in the clay to 11·79 per cent. Calculating from these data, he tells us that the sandy soil had yielded the crop 13·83 lb. of water per cubic foot of soil, while the same volume of the clay soil had yielded only 12·5 lb. Experience in the United States supplies abundant

examples of the efficient supply of water to crops in semi-arid regions by soils destitute of clay, but consisting of fine particles of silt and sand.

Th. Schloesing junior (*Compt. rend.*, cxxv. 824) has called attention to the greater speed with which sulphate of ammonium nitrifies in a sandy soil than in one containing much clay, when both contain a similar moderate proportion of water. His experiments were made with artificial mixtures of sand and clay in various proportions, including a small quantity of chalk; the same percentage of water was added to each mixture. All the soils were in a loose condition, and abundance of air was thus provided. He concludes that the different rate of nitrification is mainly due to the different thickness, and therefore availability, of the water film coating the particles of the various mixtures. By increasing the percentage of water in the soils containing most clay the rate of nitrification was raised to that observed in sandy soils.

A soil of coarse sand will show to best advantage in a season of frequent slight showers. These small supplies of water may be as thoroughly retained by the sand as by clay, while they will penetrate the sand to a much greater depth, and more effectually supply the needs of plant roots.

Percolation. The conditions which affect the passage of water through the soil require some remark. Percolation is of course greatest where the retention of water is least; the characters of the soil which produce little retention are thus favourable to a large percolation, and vice versa.

King (*The Soil*, 171) determined the rate at which water would pass through columns of sand of different degrees of fineness, columns of clay loam, and black marsh soil. The columns were one-tenth of a square foot in cross section, and

fourteen inches high. A head of water two inches in height was maintained on the top of each column throughout the experiment. The results were as follows :—

Inches of Water passing in twenty-four hours

Meshes per inch of Sieves used to prepare Sands.				*Clay Loam.*	*Black Marsh.*
40 – 60	60 – 80	80 – 100	100 –	...	...
Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*
301	160	73·2	39·7	1·6	0·7

This series of results serves excellently to illustrate the fact, that the finer are the particles of a soil the slower will be the rate of percolation through it. King remarks that the whole of the rates of percolation observed are far above what the same soils would yield in the field ; this is owing to the shortness of the columns used, the absence of air in the interstices, and the considerable head of water maintained.

King (11*th Wisconsin Report*, 285) has also determined in great detail the rate at which water drains from saturated sands of various degrees of fineness. The sands, prepared as before, were filled into tubes 8 ft. long and 5 inches in diameter ; each column was completely saturated with water from below, and drainage was then allowed to commence. All the sands contained nearly the same proportion of water when saturated. Air was allowed to enter at the top of each column, but precautions were taken to prevent evaporation.

The amount of percolation in the first hour shows in the most striking manner the different behaviour of the coarsest and finest sand. The finer sands, retaining so much more water at first, discharge after the first hour a little more than the coarsest. At the end of nine days, regular percolation had ceased in all the columns ; but from time to time slight per-

colation recommenced and was duly recorded, the whole experiment lasting for 268 days.

Table XIII

WATER DRAINING FROM EIGHT FEET OF SATURATED SANDS, PER 100 OF DRY SAND (KING)

	Meshes per inch of Sieves used to prepare Sands.		
	20 – 40	60 – 80	100 –
	Water per cent.	Water per cent.	Water per cent.
One Hour	9·6	6·6	1·4
One Day	13·8	11·8	6·3
Three Days	14·5	12·5	7·5
Nine Days . . .	15·3	12·9	8·4
268 Days	16·4	13·6	9·3

During the intermittent percolation of the last 259 days the sands lost from 6·56–9·15 lb. of water per square foot, or considerably more than one inch of water [1]. This intermittent percolation deserves attention; it is doubtless due to the varying temperature and pressure of the atmosphere. A rise in temperature will act in several ways to start percolation in a soil in which the water had previously reached a state of equilibrium. As the temperature rises water becomes less viscous and its surface tension diminishes; drainage therefore recommences in the sand column, the water films coating the upper fully drained portion becoming thinner and some of the water passing downwards. The amount capable of being held in the capillary passages at the foot of the column is also diminished. A rapid expansion of the air within the column will also cause the expulsion of a part of the water collected

[1] One inch of water on a square foot is roughly 5·2 lb.

at the lower end (see Table XI). A fall in temperature will cause this new percolation to cease and will tend to bring about a redistribution of water towards the surface. A sudden fall in the barometer may act on the air contained in the column in the same manner as a rise of temperature. These changes all occur in a natural soil, though the results from them are not generally large; we shall have to refer to them again when we speak of the movements of underground water (p. 129).

Percolation, without a constant supply of water above, is only possible if air can enter the soil to take the place of the water leaving it. Percolation may be stopped for a time by a slight rain falling on the surface and closing the air passages. This has been observed in the case of the Rothamsted drain-gauges.

King has made some experiments upon the influence of temperature upon the rate of percolation through sand, a constant water supply being provided. He found that a rise of temperature from 9° to 24° C. increased the rate of percolation 50 per cent. This result he thinks may possibly be above the truth. According, however, to Briggs' calculation, the experimental results obtained by King are precisely those which might have been predicted from the known diminution of the viscosity of water with a rise in temperature. It is obvious therefore that soils will drain much more freely in summer than in winter.

The resistance of clay to the percolation of water is a fact with which all are familiar; the resistance is absolute when the clay is in a puddled condition, that is when it has been reduced to a mass of single particles. This resistance may be greatly modified by the coagulation of the clay with lime

(Sachsse and Becker's experiment, p. 33), and by the formation of compound particles. The resistance of puddled clay to the passage of water is due in great part to the extreme fineness of the particles, and to the great resistance which has to be overcome in passing between them ; but there can be little doubt that a considerable part of the difficulty is due to the colloid constituent of the clay, which occupies the interspaces with a jelly-like substance, and thus immensely increases the resistance offered to the passage of water. The coagulation of this colloid profoundly alters the character of the clay.

In the case of a heavy loam or clay soil, under natural conditions, percolation is much facilitated by the presence of channels formed by worms, or by the roots of plants; and by the occurrence of fissures, either originating in times of drought or natural joints in the formation. Rain may pass down these passages before the soil is saturated ; summer drainage on such soils is often chiefly of this character.

The amount of water passing through a soil is measured by means of drain-gauges or lysimeters; an instrument of this kind was constructed by Dalton in 1796, and the same method of investigation has since been employed by many observers. Most drain-gauges consist of cylinders or square frames artificially filled with soil, and usually 3 ft. deep, with an arrangement below for collecting and measuring the water which passes through. The three drain-gauges at Rothamsted, constructed in 1870 (*Jour. Roy. Agri. Soc.* 1881, 269), consist of rectangular blocks of undisturbed soil, isolated by walls of brick set in cement, and supported below on perforated iron plates, below which is placed a metal funnel, so that all drainage water can be collected and measured. The three

blocks of soil have the respective depths of 20, 40, and 60 inches; the surface area of the soil is in all cases $\frac{1}{1000}$th of an acre. The soil is a heavy loam containing many flints, having a clay subsoil. The surface of the soil is kept free from weeds, and undergoes no tillage.

The average amounts of monthly percolation during twenty years, as shown by the shallowest and deepest soil of the Rothamsted drain-gauges, will be found in Table XIV. Further results from these and other drain-gauges will be found on pp. 109, 122.

TABLE XIV

AVERAGE MONTHLY PERCOLATION THROUGH BARE SOILS TWENTY INCHES AND SIXTY INCHES DEEP, ROTHAMSTED

	Rainfall.	Percolation.		Percolation per cent. Rain.	
		20-inch Gauge.	60-inch Gauge.	20-inch Gauge.	60-inch Gauge.
	inches.	inches.	inches.		
January	2·51	1·96	2·06	78·1	82·1
February	2·04	1·44	1·44	70·6	70·6
March	1·74	0·80	0·86	46·0	49·4
April	2·21	0·67	0·68	30·3	30·8
May	2·28	0·60	0·59	26·3	25·9
June	2·52	0·63	0·60	25·0	23·8
July	3·03	0·84	0·77	27·7	25·4
August	2·45	0·56	0·50	22·9	20·4
September	2·86	0·96	0·75	33·6	26·2
October	3·20	1·78	1·50	55·6	46·9
November	3·03	2·24	2·05	73·9	67·7
December	2·42	1·90	1·81	78·5	74·8
Whole Year	30·29	14·38	13·61	47·5	44·9

As the amount of evaporation from the soil is far greater in summer than in winter, the amount of drainage naturally

varies in a contrary manner. The season of active drainage through a bare uncropped loam is shown by the figures in the table to commence in October and to continue till the end of February. In a climate having a severe winter, as Canada, this heavy winter drainage will not occur, but in its place there will be a large amount of drainage in April when a thaw occurs. During the spring thaw in such climates large quantities of snow water will however flow away over the surface, when the inclination allows of it, the frozen condition of the soil hindering percolation. The amount of annual percolation is thus considerably diminished in a severe winter climate.

It will be noticed that the deep and shallow soils both deliver the same amounts of drainage at the end of winter, the deepest soil continuing draining longest. In summer and autumn the shallow soil yields the most drainage, the supply of water to its surface by capillary action, and consequently the amount lost by evaporation, being somewhat smaller than in the case of the deeper soil.

The amount of water passing through a soil is so largely influenced by the rate of evaporation from its surface, that it will be necessary to return to the subject again when the conditions of evaporation have been considered (p. 125).

CHAPTER III

RELATIONS OF SOIL TO WATER (*continued*)

Capillary Action—Evaporation from Bare Soil—Influence of Crop on Evaporation—Underground Water—Wet and Dry Soils—Amelioration of the Physical Properties of Soil.

Capillary Action. The rapid movements of water and other liquids in porous bodies is a fact with which all are familiar; the rise of water in a lump of sugar, the spreading of a drop of water in blotting paper, the rise of oil in a wick, are all examples of capillary action. The typical instance, which supplies the name for the whole of the phenomena, is supplied by the rise of liquids in narrow tubes. The height to which water will rise in glass tubes of various diameters is as follows:—

Height to which Water at 0° C. rises in glass tubes

Tube	1 mm.	diameter, water rises to	15·336 mm.
„	0·1 „	„ „ „ „	153·36 „
„	0·01 „	„ „ „ „	1533·6 „

The height is thus greater the narrower is the tube. A reduction of the diameter to one-tenth causes the water to rise to ten times the previous height. The height to which a liquid rises is somewhat diminished by an increase in temperature.

The rise of a liquid in a narrow tube or passage is only a particular manifestation of the familiar adhesion between a solid and liquid which is seen when a stick or clean stone

withdrawn from water comes out with a wet surface. Water rises in a glass tube, or through the spaces existing in a mass of sand, simply because the attraction of the surface particles of the glass or sand for the particles of the water is at first greater than the attraction of gravity; the rise of water ceases when the mass of water in the column reaches such dimensions that the attraction of gravity balances the surface attraction of the glass or sand. The surface attraction is greater, and the quantity of water raised larger, the wider the tube; but the height to which the water is raised is greater the narrower the tube; because while the attracting surface simply diminishes in the same ratio as the diameter of the tube, the volume of water within the tube (and thus the weight to be raised) diminishes as the square of the diameter, and the less weight is thus carried to a greater height.

The same forces which occasion the rise of water in a tube will determine the distribution of water over moist surfaces, and this aspect of the subject is of considerable importance for the correct understanding of the movements of water in a soil. It is only when the interspaces of a soil are filled or nearly filled with water, that an uninterrupted passage of water through tubes of varying size, shape, and direction can take place. In the case of a fully drained soil of open texture, or consisting of coarse particles, the particles are merely covered with a water film, and it is only at the points of contact between the particles that anything of the nature of a tube is to be found. The distribution of the water over the surfaces of the moist particles is however governed by the same laws which control its behaviour in soil tubes.

Briggs (Mechanics of Soil Moisture, *Soils*, *Bull.* 10) has

given a very clear account of the condition and behaviour of water in a drained soil. The retention of water on the surface of soil particles, in spite of the opposing force of gravitation, is due to what is called 'surface tension.' The surface of the film of water encircling a soil particle is really in the condition of an elastic membrane exerting a very considerable pressure; the water is in consequence firmly held

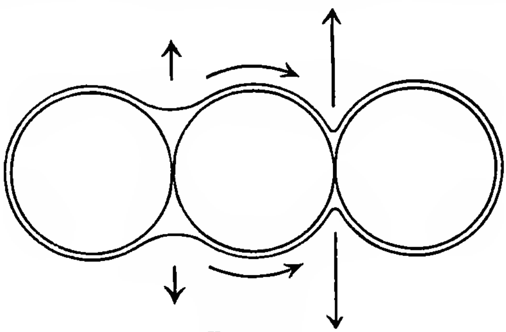

FIGURE 3.

against the soil particle. In a fully drained soil there exists a condition of equilibrium between the force exerted by surface tension and the force exerted by gravity. If the films of water became thicker and heavier, a part of the water would gradually pass downwards in obedience to the attraction of gravity. If the films became thinner they would acquire the power of absorbing and retaining fresh supplies of neighbouring water.

In Figure 3 will be found the diagram used by Briggs to illustrate the transference of water from a wetter to a drier portion of the soil, a transference which in this illustration depends entirely on the surface tension of the water, and not upon the existence of connecting tubes.

The three particles of soil, which lie in contact, are each

surrounded by an elastic film of water exerting a considerable pressure towards the centre of the particle. The result of this state of tension is that an *outward* pressure exists on the surface of the thicker portion of the film lying at the points of contact between the particles. This outward pressure is greater the thinner is the film on the adjoining particles. If therefore moister and drier particles are in contact, water will pass from the first to the last till an equilibrium of surface tension is established throughout the system. The figure shows this transference of water in action; the arrows indicate the direction of the pressure in the different parts of the system.

Water thus tends to distribute itself in a soil, either through capillary passages, or by the slower process of surface distribution. When these operations are assisted by gravitation, as when rain falls on a dry soil, the movement of the water becomes rapid. When these operations are opposed by gravitation, as when a soil dries at the surface and is still wet below, the movement is retarded, and the amount of possible work is limited, as in the case of the rise of water in a glass tube, by the final neutralization of the attractive forces by the increasing weight of the column of water lifted.

The height to which water will rise in a soil by capillary action depends primarily on the size of the soil particles, and the closeness of their packing. When a soil is composed of very coarse particles, as in the case of gravel, the interspaces are so wide and the points of contact so few, that capillary action has little influence on the distribution of water throughout the mass. In the case of sands and loams the interspaces become sufficiently narrow for the action to

assume practical importance. Capital illustrations of the influence of various conditions on the height to which water is raised, and the quantity lifted, are furnished by the experiments of Johnson and Armsby with loam and emery (*Connecticut Exp. Stat. Rep.* 1878, 83); the latter substance was selected because it can be procured in commerce graded in various degrees of fineness.

A loam was separated by sifting into particles of three grades. Tubes fourteen inches long and two inches in diameter were filled with these soils; the lower ends of these tubes were then placed in water. The quantity of water evaporated by each soil in 150 days per square inch of surface was as follows:—

Average Diameter of Soil Particles.			*Water Evaporated per square inch.*
3·0 mm.	...	...	49·2 grams
1·0 ,,	...	...	73·8 ,,
less than 0·25 ,,	...	...	153·8 ,,

We see that as the size of the soil particles diminished there was a large increase in the quantity of water brought to the surface. In the case of the two coarser materials the amount of water raised was insufficient to preserve a moist condition at the surface; the action in these cases was thus mainly due to a mere surface distribution of water.

The next experiment we quote shows the influence of varying height on the quantity of water raised. The trials were all made with emery of one kind, the average diameter of the particles being 0·229 mm. The experiment lasted twenty-five days.

Relative Heights of the Columns.				*Water Evaporated.*
1	...	...	...	133·9 grams
2	...	...	...	118·2 ,,
3	...	...	...	112·0 ,,

The highest column ($13\frac{1}{2}$ inches) was apparently saturated with water to the top; notwithstanding less water was evaporated than by the shorter columns, the water rising more slowly the greater the length of the column.

In the next experiment the height of the column was in all cases fourteen inches, but the tubes were filled with emery of various degrees of fineness. The trials lasted eighty-four days.

Average Diameter of Particles.			*Water Evaporated per square inch.*
0.443 mm.	...	...	40.3 grams.
0.356 ,,	...	...	138.4 ,,
0.229 ,,	...	...	155.1 ,,
0.140 ,,	...	...	150.6 ,,
0.076 ,,	...	...	144.7 ,,

It will be seen that the largest quantity of water is brought to the surface by the emery of intermediate fineness (diam. 0.229 mm.), and that as the particles become either coarser or finer the quantity is diminished. The coarser particles failed because the surface was never saturated with water; the coarsest emery could saturate at 8 inches, the next coarsest at 11 inches. The finer particles failed because of the slower movement of the water in their passages. Had the column been shortened, one of the coarser emeries would have evaporated most water; had it been lengthened one of the finer would have appeared the most effective. This is an important lesson. For every distance of the surface from the water supply there is a particular size of soil particles which will bring up the largest quantity of water, and in the case of moderate distances it is by no means the finest particles which are the most effective.

The laboratory experiments on the capillary power of some Californian soils made by Loughridge (*California Exp. Stat.*

Rep. 1892–3–4, 91) are especially instructive as the mechanical analysis of the soils is also given. The experiments were made in copper tubes 1 inch in diameter; the tubes were in 1 ft. lengths, fitting into each other. One side of the tube was glass so that the contents might be observed. The bottom tube was closed at its lower end with muslin. The tubes were filled with air-dried soil, stirred in the tube with a wire, and made firm by a slight tapping on the table.

The composition of the soils, and the details of the rise of water in them, are shown in Tables XV and XVI.

Table XV

MECHANICAL ANALYSES OF FOUR CALIFORNIAN SOILS (LOUGHRIDGE)

	Clay.	Fine Silt.	Coarse Silt.	Fine Sand.
1. Sandy Soil . .	2.82	3.03	3.49	89.25
2. Alluvial Soil .	3.21	5.53	15.42	72.05
3. Silty Soil . .	15.02	15.24	25.84	45.41
4. Adobe Soil . .	44.27	25.35	13.47	13.37

Table XVI

RISE OF WATER IN FOUR CALIFORNIAN SOILS (LOUGHRIDGE)

No.	1 Hour.	6 Hours.	1 Day.	2 Days.	6 Days.	12 Days.	26 Days.	125 Days.	195 Days.
	in.	in.	in.	in.	in.	in.	in.	in.	in.
1	8	12½	14	15	16½				
2	9½	19	27	30½	35	38	41	47	
3	2	9	13	17	20½	25	31½	41	50
4	1½	6	10½	14½		23	26½		46

The first thing to note is the extremely rapid rise of water in the two coarser soils, a height of 8–9 inches being reached during the first hour, while the water in the two stiffer soils had only reached 1½–2 inches. The first soil has a very simple constitution, very little clay or silt being mixed with the sand; the rise here is nearly completed in the first day, and is quite finished in six days. The second soil contains hardly any more clay than the first, but there is a good deal of silt, which, occupying the interspaces between the sand, entirely alters the behaviour of the soil to water. At the end of the first day the water has risen to nearly double the height reached in the first soil. After six days the rise becomes very slow, and getting slower and slower, a height of 47 inches is finally reached in 125 days, 42 days having been consumed in accomplishing the last inch. The rise of water in the silty soil is at first much slower than in the two previously mentioned, but the rate of progress is well maintained, and 50 inches is finally reached in 195 days. The heavy adobe soil is for a long time far behind the others, but like No. 3, it goes on when the others have stopped, and the water at last reaches 46 inches in 195 days. The rise of water in clay soils is thus very slow, and the considerable height finally reached is no proof of energetic capillary action. The colloid ingredient of the clay is doubtless a hindrance to the rapid passage of water, though perhaps helping finally to carry the water to a greater height. Capillary action is most active in the case of the alluvial soil, made up of fine sand and silt; in soils of this class, more than in any other, will this action be of substantial benefit to a crop.

At the close of the experiment the percentage of water

contained in the soils at different heights in the columns was determined with the following results:—

Water per 100 of Soil at different heights

	1 in.	6 in.	12 in.	24 in.	36 in.	47 in.
1. Sandy Soil ...	24·3 ...	14·2 ...	3·9			
2. Alluvial Soil ...	36·6 ...	35·0 ...	32·5 ...	21·4 ...	12·0 ...	4·3

Thus the greater the height in the column, the smaller is the quantity of water found. As we ascend, the wider interspaces would be found unfilled, and at last the particles will be merely coated with a thin film of water. The supply of water at extreme heights is thus very feeble, and it may well be doubted whether the gain of water at these elevations is not due rather to the condensation of vapour rather than to an actual ascent of liquid water.

In all experiments made with dry soils the upward movement of the water is retarded by the fact that air has to be expelled from all the passages. Some dry soils are also difficult to wet, the particles remaining obstinately coated with a film of air; this is frequently observed in the case of dried marsh soils.

The question whether the quantity of water raised by capillary action in ordinary soils is sufficient to furnish a substantial supply to field crops has been greatly elucidated by the experiments made by King at Wisconsin.

In the first experiment (*Wisconsin 6th Rep.*, 203) the conditions were made especially favourable to capillary action. A cylinder 4 ft. in height and 1 ft. in diameter, which could be supplied with water from below, was first partly filled with water, and the fine sand from the Wisconsin subsoil was then dropped in, each addition of sand being well stirred in the water. A column of sand 4 ft. high was

finally obtained free from air and perfectly saturated with water. The water level was then lowered till it was 1 ft. below the surface, and was then maintained at this point. The surface of the cylinder was then exposed to a strong current of air (the velocity of which was measured) for eight days, and the quantity of water evaporated from the surface of the sand was ascertained. The water-level was then successively reduced to 2, 3, and 4 ft. below the surface, and at each stage the quantity of water evaporated at the surface was ascertained; each experiment lasted from ten to twenty-four days. The trials were afterwards repeated, using in place of sand a surface loam (*Wisconsin 7th Rep.*, 151). The results were as follows:—

Water evaporated daily per Square Foot

	Water Level 1 ft. below Surface.	*Water Level 2 ft. below Surface.*	*Water Level 3 ft. below Surface.*	*Water Level 4 ft. below Surface.*
	lb.	lb.	lb.	lb.
Fine Sand ...	2·37 ...	2·07 ...	1·23 ...	0·91
Clay Loam ...	2·05 ...	1·62 ...	1·00 ...	0·90

The amount evaporated in each case thus diminished as the distance of the water-level from the surface increased. Towards the close of the trials a slight white crust formed on the surface of both sand and loam, this was removed in the case of the loam, the rate of evaporation then rose to 1·27 lb. per day.

The quantity of water raised daily a distance of 4 ft. by capillary action was thus at least 1 lb. per square foot, equal to a supply of about 1 inch of rain in five days, a quantity quite sufficient for the most luxuriant growth[1].

[1] The surface of a soil may be treated both so as to favour or retard evaporation. When the surface of the wet sand was cut across with a knife

The experience at Wisconsin shows, however, that with the same sand and loam in their natural condition in the field no such large rise of the subsoil water occurs. The experimental ground of the station is near Lake Mendota, and the water level in the subsoil is, at different seasons of the year, between four and seven feet below the surface. In seasons of drought crops often suffer considerably on this land from deficiency of water, although at the time the water level in the subsoil may be only five feet below the surface.

The much smaller results from capillary action in natural soils are doubtless due to their more irregular texture as compared with the artificially prepared columns employed in laboratory experiments. In the natural soil the capillary passages are less uniform in size, and are always more or less filled with air. The percentages of water found by Loughridge in the alluvial soil (p. 100) wetted by a rise of water from below, show that the soil was less than two-thirds saturated at a height of 2 ft., and one-third saturated at a height of 3 ft. above the water level, more than 125 days after the commencement of the experiment. It is in a saturated soil that water moves with the greatest freedom, the largest passages forming the most effective channels when the quantity of water moved is regarded. In a well drained soil only the finest passages remain full of water, and these will be often interrupted by wider spaces full of air. The movement of water is thus limited

in many places to the depth of two inches, the rate of evaporation rose from 0·95 lb. per square foot to 1·76 lb. When, on the other hand, the uppermost two inches of the sand were removed, and then replaced in a loose condition, the rate of evaporation fell to 0·63 lb. per square foot. For a further discussion of this point see p. 113.

to the redistribution of the water coating the particles, and the movement then becomes very slow.

Another reason for the slow movement of water in natural soils lies in the fact that the water has to be drawn from moist soil and not from free water. A fine passage tries to fill itself at the expense of a wider one, a thin film grows at the cost of a thicker one, and the result in each case is merely the difference in their respective powers. This is one chief reason of the great falling off in the rate of rise as the column of soil lengthens; we have already seen that an alluvial soil (p. 99) took forty-two days in accomplishing the 47th inch. It is evident that when rain and percolation have ceased, the movement of water from a wetter to a drier part of the soil must be greatly hindered by the reluctance of the wetter soil to part with its water. Even when, as at Wisconsin, the water level in the subsoil is fairly near the surface, the rise of water in the soil is by no means free from this hindrance, the so-called water level being merely the surface of a mass of saturated soil.

An excellent example of the slow movement of water in a dry natural soil is afforded by another of King's experiments (*Wisconsin 7th Rep.*, 143). After the dry summer of 1889 a soil was sampled on Oct. 28, to a depth of 5 ft., and the percentage of water at different depths determined. A portion of the ground was then effectually protected from rain and snow and left in this condition till April 14 in the following year, when the soil was again sampled as before, and the water present determined. For results obtained see Table XVII.

The covered soil had apparently gained no water from below during the winter months, but had on the contrary actually lost some water by evaporation. The soil open to

the weather had gained much water, but clearly from above. In this case the water level was about 30 ft. below the surface.

TABLE XVII

WATER PER 100 DRY SOIL, COVERED AND UNCOVERED, AT DIFFERENT DATES (KING)

	Original Soil.	Soil Covered.	Soil not Covered.
	Oct. 28, 1889.	Apr. 14, 1890.	Apr. 14, 1890.
1st ft. Sandy Clay . . .	4.03	3.32	20.23
2nd ft. Red Clay . . .	10.07	6.68	20.01
3rd ft. Clay and Sand . .	9.11	6.32	8.32
4th ft. Sand and Gravel .	4.35	3.71	8.63
5th ft. Sand and Gravel .	4.53	5.08	6.07
Mean	6.42	5.02	12.65

A comparison of the results given by the deepest and shallowest of the Rothamsted drain-gauges also affords an example of the small influence of capillary action in bringing water to the surface. Each drain-gauge consists of a rectangular mass of heavy loam, with flints, of the area of $\frac{1}{1000}$ of an acre; the depth of the shallowest mass of soil is 20 inches, of the deepest 60 inches. The deepest soil has thus a subsoil of 40 inches to draw upon, which is wanting in the case of the shallowest soil. On an average of twenty-four years the annual evaporation from the deepest soil has only exceeded that from the shallowest by 0·6 inch; this probably represents the quantity of water brought to the surface from below a depth of 20 inches.

According to various published experiments the presence of certain salts increases the rapidity of movement in capillary

tubes, and the height finally reached, while the soluble organic matters present in soils have a contrary effect. The results at present obtained are not, however, sufficiently definite to justify any practical conclusions on the subject.

The practical effect of capillary action in raising water to the surface of the soil, or to the level occupied by plant roots, has apparently been a good deal exaggerated; its influence on the distribution of water in the soil is nevertheless very large. We must recollect that capillary action is by no means confined to the raising of water, its effects are indeed most limited in this direction as it is then opposed by the force of gravity. The greatest manifestation of capillary action is seen in the distribution of water in a dry soil after a shower of rain. It is the surface attraction of the particles of the soil for water which causes the rain to be sucked down, with the energy with which we all are familiar, and carried into the finest passages and remotest portions of the soil.

When the percolation produced by the attraction of gravity has ceased, the system of soil and water is in a condition of equilibrium, the nature of which in the case of sandy soils is well shown by the upper half of Table XI. If water is now removed from any portion of this system by root-action, or by evaporation at the surface, the equilibrium is upset, and the water coating the particles is induced by the local alterations in its tension to redistribute itself, and regain once more the state of equilibrium. In the case of coarse sands, this redistribution consists mainly in the movement of the film of water coating the particles, and such movement will be extremely slow; it will however persist at a diminishing rate till the amount of water in the soil is reduced nearly to the proportion of so-called

hygroscopic water which it is capable of holding. This redistribution of water will take place more easily when the loss is occasioned by means of roots, because in this case the whole action is beneath the surface, and the soil particles never become perfectly dry. When perfectly dried and coated with air, the renewal of a film of water becomes more difficult. It is evident that this redistribution of water in the soil will be effected to a greater extent (because more easily) by bringing a fresh supply of water from above, or from the side, than from below; indeed in the case of coarse sands, the supply from below must be extremely small.

The case of a silt or loam is quite different; here, when percolation has ceased, the soil may remain nearly saturated with water throughout its whole depth. When this condition of equilibrium is disturbed, the movements of soil-water re-establishing it will at first be far more vigorous than in the previous case, the passages in the soil being in this case more or less filled with water. The facilities for procuring a considerable supply of water from below, will in this case be largely increased. The advantages mentioned do not however continue to increase as the size of the soil particles diminishes; we have in fact already pointed out (pp. 86, 97) that excessive fineness of particles, while increasing the water-holding power of a soil, greatly diminishes the freedom of movement of the soil water. Stiff clay soils, when in a puddled condition, notwithstanding the large amount of water they may contain, are quite incapable of efficiently supplying the wants of a plant; the roots take water from the soil they are in contact with, but this water is replaced so slowly from the surrounding soil that the plant may die of drought. The maximum advantages of capillary action are apparently to be

found in fine-grained soils, such as constitute alluvial deposits, rather than in those rich in clay.

Soils which have a permanent supply of water four feet below the surface are naturally in a position to secure exceptional advantages from capillary action. Such a circumstance is of course uncommon; it should result in a high condition of fertility.

Evaporation from Bare Soil. When water is converted into vapour, there is always a disappearance of heat, which performs the work of separating the molecules of water, and lifting them as vapour. Without the presence of available heat, no evaporation can take place. By heat we do not mean temperature. On a cloudy hot summer's day there may possibly be no evaporation, while on a cold winter's day evaporation may be active. If the atmosphere surrounding the moist surface is saturated with water vapour, no evaporation will occur without a further increment of heat, such in fact as might be afforded by sunshine. If, however, the atmosphere is only partially saturated, evaporation of water will take place however low the temperature; and the temperature of the water and air will fall till the atmosphere becomes saturated, when evaporation will stop. If the unsaturated atmosphere is continually renewed, as in the case of a drying wind, evaporation will continue; the heat demanded for the formation of vapour being supplied by the cooling of the air and water. The popular statement that evaporation produces cold, is thus quite true. If one pint of water is evaporated from 97 pints, the remaining 96 pints will have fallen 10° F. in temperature, or an equivalent amount of heat must have been supplied by surrounding bodies.

The best way of approaching the subject of evaporation

from soil is to consider in the first place the simpler case of the evaporation from a water-surface. Greaves (*Proc. Instit. Civil Engineers, Feb.* 29, 1876) has determined for many years the evaporation from a tank having one square yard of surface; the tank was kept floating in a stream of water, the temperature of the water in the tank was thus similar to that of the bulk of water surrounding it. The average amounts of evaporation he observed were as follows:—

TABLE XVIII

EVAPORATION FROM A WATER SURFACE NEAR LONDON. AVERAGE OF FOURTEEN YEARS (GREAVES)

	Rainfall.	Evaporation.	Evaporation Plus or Minus Rainfall.
	inches.	inches.	inches.
January	2.87	0.76	−2.11
February . . .	1.60	0.60	−1.00
March	1.94	1.07	−0.87
April	1.43	2.10	+0.67
May	2.06	2.75	+0.69
June.	2.21	3.14	+0.93
July	1.77	3.44	+1.67
August	2.33	2.85	+0.52
September. . . .	2.35	1.61	−0.74
October. . . .	2.73	1.06	−1.67
November	2.02	0.71	−1.31
December	2.42	0.57	−1.85
Whole Year . .	25.73	20.66	−5.07

We see that the average amount of evaporation from the water-surface has been 20·66 inches in the year. The rate of evaporation is very different in the different seasons. From November to February the evaporation is only 0·6–0·7 inch per month. After February a rapid rise sets in, the largest

evaporation being reached in June and July, namely 3·14 and 3·44 inches. After July the evaporation again diminishes till the winter minimum is reached. In five months of the year the evaporation exceeds the rainfall, but in the whole year it is less than the rainfall by 5 inches.

The rate of evaporation from a perfectly saturated soil destitute of vegetation, is somewhat greater than from a water-surface, the rough soil exposing a larger area of surface than the level surface of the water. The average evaporation from the bare loam in the Rothamsted drain-gauges (Table XXII) during six winter months (4·8–5·2 inches) is quite similar to that from a water-surface (4·8 inches), but in the six summer months the evaporation from the Rothamsted loam (11·1–11·5 inches) is distinctly less than that from water (15·9 inches), as the soil is at this season seldom saturated.

The annual evaporation from the Rothamsted bare loam is singularly unaffected by the amount of the rainfall. The following table shows the results obtained during the first

TABLE XIX

EVAPORATION AND PERCOLATION FROM BARE LOAM, ROTHAMSTED, DURING NINE YEARS

Season Oct.-Sept.	Rainfall.	Soil 20 inches deep.		Soil 60 inches deep.	
		Evaporation.	Percolation.	Evaporation.	Percolation.
	inches.	inches.	inches.	inches.	inches.
1873–4	22·9	17·3	5·6	18·9	4·0
1871–2	26·3	18·4	7·9	19·1	7·2
1870–1	29·3	18·1	11·2	22·4	6·9
1874–5	30·8	18·3	12·5	20·0	10·8
1872–3	31·6	16·6	15·0	19·4	12·2
1877–8	32·6	18·0	14·6	17·9	14·7
1875–6	34·2	18·0	16·2	17·4	16·8
1876–7	35·8	18·3	17·5	17·4	18·4
1878–9	42·7	17·2	25·5	17·5	25·2

nine years after the establishment of the gauges. The years are arranged in the order of their rainfall.

The rainfall in the seasons mentioned shows a large range of variation, 22·9–42·7 inches; but the amount of the evaporation, though varying somewhat from year to year, seems quite independent of the amount of rain. The large evaporation credited to the deeper soil in 1870–1, is doubtless above the truth. The gauges were constructed in the dry summer of 1870, and the blocks of soil were during the construction suffering evaporation from the side as well as from the surface.

The comparative constancy of the rate of evaporation from the bare soil is doubtless due to the fact that the two factors which tend to produce a large evaporation do not occur together. In a wet season there is an ample supply of water to be evaporated, but evaporation is hindered because the sky is cloudy and the temperature low; while in a fine hot season evaporation is checked as soon as the surface of the soil has dried, and its amount is controlled by the scantiness of the rainfall[1].

All descriptions of soil will evaporate a similar amount of water when they are in a perfectly saturated condition. In the case of very permeable soils, consisting of coarse particles, this condition continues only a short time after rain has ceased; when this point is passed, the capacity of a soil to evaporate water will largely depend on the quantity of water it is capable of retaining near the surface.

[1] The amounts of evaporation shown in Table XIX have not been maintained in subsequent years (compare Table XXII). This diminution of evaporation, with its consequent increase in percolation, is apparently due to the fact that the soils have been left undisturbed though kept free from weeds, and their surface is now more occupied by stones than at first; a slight growth of moss hss also taken place.

An extreme instance of the behaviour of a very permeable soil is furnished by the drain-gauge filled by Greaves with fine gravel, prepared by sifting through a screen with eleven wires in two inches (Table XXII). In this very coarse soil, with an extremely free percolation, the winter evaporation is only 1·2 inches, and that for the whole year 4·2 inches. The amount of evaporation is thus largely diminished when only a small quantity of water is retained near the surface.

The speed with which a soil dries depends greatly on its mechanical condition. When a soil is in an open, loose condition, and is thus readily permeable to air, evaporation may go on within its mass as well as on its external surface. A soil thus dries quicker at the surface when in the crumbly pulverulent state known as 'good tilth,' and the general effect of tillage is in the same direction. The practice of ploughing clays in autumn, and leaving the land in ridges through the winter, not only yields a better tilth, but also a drier seed-bed when the land is harrowed in spring. Soils composed of coarse particles not only retain but little water, they also dry quickly at the surface.

Evaporation from the soil is greatly diminished when it is shaded from the sun's rays, and protected from wind. The effect of protection from sun and wind in diminishing evaporation, is seen most strikingly in the case of a forest soil. Ebermayer (*Lehre der Waldstreu*, 182) describes experiments made during five years, at six forest stations, on the comparative amount of evaporation from artificially saturated soils within the forest, and freely exposed without. During the six months, April to September, the evaporation within the forest was on an average only 47 per cent. of that observed from similar soil in the open. Land covered by a

growing crop is generally moist on the surface. This maintenance of a moist surface is of importance to fertility in many ways; it is only under this condition that the nitrifying and other organisms can discharge their functions actively.

Protection from wind by means of hedges diminishes the rate of evaporation. King (*Wisconsin 11th Rep.*, 309) determined the rate of evaporation from a known surface of filter paper, constantly supplied with water (Piche's evaporometer), at various distances from a hedgerow, and other forms of shelter. The evaporometer was placed 1 foot above the ground. The trials were made on different days, mostly in bright sunshiny weather. The following figures show the number of cubic centimetres of water evaporated in the same time at various distances from shelter.

Water evaporated at various distances from shelter

	20 ft.	100 ft.	150 ft.	200 ft.	300 ft.	400 ft.
	c.c.	c.c.	c.c.	c.c.	c.c.	c.c.
Oak Grove	11·1	14·3	...	15·7	18·5	18·5
Hedge	10·3	...	12·5	...	13·4	
Clover Field	9·3	...	12·1	...	13·0	

The effect of the Oak Grove was thus felt at a distance of more than 200 ft., but beyond 300 ft. its influence ceased. The influence of the scanty hedge, and of the clover field, was clearly felt at distances exceeding 150 ft. The effects of shelter, even of so low a kind as that afforded by growing clover, are clearly considerable; they are due partly to the diminished velocity of the wind at the surface of the soil, and partly to the fact that the wind is less dry after passing through the shrubs and plants forming the shelter. On both these points King has made experiments.

The evaporation from the soil may be considerably dimin-

ished by protective coverings. Stones are effective in this way; on turning over a large stone in summer time the ground will generally be found moist underneath[1]. Mulching—or covering the soil with a layer of farmyard manure, straw, dead leaves, or cocoa-nut fibre—is extremely effective, the surface being in this way thoroughly protected from both sun and wind. In the field, valuable results may be obtained by repeated shallow cultivation, by which a few inches of loose soil are permanently maintained at the surface during summer time; this plan is largely followed in hot climates, and on its use the success of the crop often depends. King has made many experiments on this point, one of which we will describe (*Wisconsin 8th Rep.*, 105). A field which had been ploughed and harrowed in the spring was divided into alternating strips, each 12 ft. wide. One set of strips was rolled on May 14, the intermediate ones were cultivated frequently to a depth of three inches. The percentages of water found at different depths during the summer were as follows:—

TABLE XX

WATER PER 100 OF DRY SOIL IN SOILS ROLLED OR CULTIVATED (KING)

	First Foot.		Second Foot.		Third Foot.	
	Rolled.	Cultivated.	Rolled.	Cultivated.	Rolled.	Cultivated.
	per cent.	per cent.	per cent.	per cent.	per cent.	per cent.
May 29	15.4	17.2	16.6	16.4	14.5	14.3
June 9	13.6	16.9	13.7	15.8	14.3	14.1
June 17	12.0	16.0	14.1	16.1	14.5	14.4
June 20	15.0	19.0	14.8	16.8	14.6	14.0
July 17	11.8	14.1	14.2	15.9	13.9	14.6

[1] The beneficial effect of stones in diminishing evaporation from the soil is greatest when the stone, as in the case of flint, is impermeable to water.

On June 17 and 20, the excess of water in the first 2 feet of the cultivated soil amounted to 1 inch. The influence of cultivation did not apparently extend to the third foot till after this date.

For this method of preserving water to yield its best results it should be commenced early. The soil at the end of winter is generally nearly saturated with water; if this water is to be preserved for the use of a crop the cultivation of the surface should be commenced as soon as a loose pulverulent layer can be obtained. The most effective plan according to King is the inversion of a thin layer of the surface soil; but as this loose surface layer requires to be renewed after each heavy rain, the use of a cultivator, horse-hoe, or grubber, is probably the most practical proceeding. In the United States it is usual to cultivate the soil in this manner between the rows of maize till the height of the crop forbids further action.

Evaporation from the soil will be more effectually checked by covering it with a mulching of manure or straw than by the method just described, but the system of mulching is one for the garden rather than the field. Trials made at the Experiment Station, New York (*New York 7th Rep.*, 180), will illustrate this part of the subject. An uncropped loam, kept free from weeds, was divided into plots; each plot was in duplicate. One pair of plots remained untouched; three others were cultivated to various depths; a fifth was covered by a 1-inch mulch of short oat straw. The experiment began in May, and continued till the end of September. Samples of soil 1 ft. in depth were taken every week by boring, and the

Stones of porous material, as many limestones, are less effective; indeed slight showers may be held in such cases by the stones, and the water afterwards evaporated without benefiting the soil.

water present determined. If we look at the mean water contents of the soils in the five weeks in the summer when the untouched soil was driest, we shall perceive most clearly the effect of these various attempts to preserve the water in the soil. The average water contents in the driest portion of the season was as follows:—

Water per 100 of Dry Soil

Untouched Soil.	*Surface kept stirred to:*			*Oat Straw.*
	half an inch.	two inches.	four inches.	one inch.
16.9 ...	19.0 ...	19.2 ...	20.3 ...	22.8

Thus keeping only half an inch of the surface stirred had a very distinct effect in preventing evaporation. The effect is increased, but not very greatly, by a deeper stirring. The maximum result is gained by the mulching with straw, one inch of straw proving far more effective than four inches of loose soil. The excess of water in one foot of the mulched soil was about equal to one inch of rain, and the influence of the mulch would doubtless be felt in both the second and third foot. Mulching should not be too deep, else slight showers will be retained by the mulch and never enter the soil. Mulching has the further advantage of effectually preventing the puddling of a clay soil by heavy rain.

The accumulation of dead leaves, seed vessels, &c., upon the soil of a forest, is of great importance to the fertility of the land, and its maintenance is one of the cares of scientific forestry. One of the benefits derived from this layer of forest litter is a diminution in the evaporation from the surface; it acts in fact as a natural mulch. Ebermayer, in the experiments already referred to (p. 111), found that the evaporation from an artificially saturated soil within the forest when covered by litter, was in the summer months only 46 per cent. of that

from a soil similarly circumstanced but without litter. Taking the evaporation from a saturated soil during the six summer months as 100 outside the forest, it amounted to 47 within the forest, and to 22 when the soil within the forest was covered by litter. The moss which covers the ground in pine forests when light gains access, acts equally as a mulch. It may, however, become injurious if it attains too great a thickness. Rain is then retained by the moss instead of entering the soil. The forest litter of dead leaves, &c., does not become injurious by accumulation, as it forms by decay a new surface soil in which the roots of trees distribute themselves. On a steep hill-side both moss and leaf-litter discharge another beneficial function, retaining the water of heavy rains which would else be lost.

The effect of tillage on evaporation has been already partly discussed. Any loosening of the texture of the surface soil favours the more rapid drying of the disturbed layer, but may, as we have seen, preserve the store of water beneath. When tillage is performed with this end in view the layer of soil loosened must be shallow; any deep tillage in summer time is out of place if the preservation of soil water is an object.

The effect produced by rolling after harrowing requires some notice. Rolling consolidates the soil, and the result is that for a time the quantity of water at the surface is increased. It is obvious that the consolidation of a loose soil increases the quantity of water in a given volume. By rolling the surface soil is also brought into more intimate contact with the moist subsoil, and the transference of water becomes easier. Moreover we have just seen that a solid soil does not become dry at the surface so quickly as a loose one, owing

to its less permeability to air. For a time then the rolled soil is moister at the surface than one left rough, and this fact is made use of by the farmer when sowing seeds in spring or summer.

King, when sowing oats and barley broadcast, and then harrowing, found that on the portions of the land rolled a greater number of seeds germinated, and that germination was quicker than on the unrolled land. When however the same seeds were drilled, and thus buried deeper in the ground, a subsequent rolling was without advantage. Rolling is undoubtedly often of great use in aiding the germination of turnip seed in a dry summer. A consolidated condition of the surface cannot however be usefully maintained. We have already seen that the amount of evaporation is in the long run greater in summer time from a consolidated soil, than from one covered by a thin layer of loose earth. This is due in part to the greater velocity of the wind over a smooth surface, and in part to the more continuous supply of water at the surface in a consolidated soil. There are also other distinct advantages from a loose surface. The farmer is thus adopting the best plan when he hoes the land as soon as the turnip plants are sufficiently grown. The hoeing is not effective merely because the plants are thinned and the weeds destroyed, its benefit is partly due to the renewal of the loose condition of the surface soil.

The effect of saline matter in the soil, or of additions of saline manures, on the rate of evaporation, must in some cases be considerable. In the experiments of Johnson and Armsby, and of King, already quoted (pp. 97, 101), the formation of a slight crust of salt on the surface greatly lessened the evaporation, presumably by choking the interstices of the

soil. From this point of view, salts of little solubility, as gypsum, should be those which most effectually hinder evaporation. Investigations on this subject are much needed; but it appears quite likely that the results obtained from manuring experiments in dry seasons are a good deal complicated by the effect of the manures on the water contents of the soil, an effect which may be as strongly manifested by a saline manure supplying little plant food as by one rich in such constituents.

The effect of farmyard manure is complicated by a variety of circumstances. Applied as a top dressing it acts excellently as a mulch, diminishing the evaporation from the soil. Ploughed in in spring or early summer, during dry weather, its effect may be to dry the surface soil considerably, its bulky nature and loose texture greatly aiding the drying effect of wind. The permanent effect of the manure is decidedly to increase the capacity of the soil for retaining water, owing to the humus produced by its decay (p. 72); but this effect is confined almost entirely to the surface soil with which the manure is mixed.

Influence of a Crop on Evaporation. We have considered hitherto the case of a bare soil, and have discussed the various circumstances influencing the amount of evaporation from it. The factor, however, which more than any other determines the rate of evaporation is the presence or absence of vegetation.

When the soil is covered by vegetation, a portion of the rain does not reach the ground, but remains on the leaves and is evaporated from them; this loss probably reaches its maximum in the case of a forest. According to Weber's observations in Switzerland, Prussia, and Bavaria, the per-

centage of rain water intercepted by the foliage and branches of various kinds of forest was as follows:—

Larch 15 per cent.	Spruce Fir 24 per cent.
Beech 19 „ „	Scotch Pine 30 „ „

The evergreen trees were thus, naturally, the most effective in retaining rain on their leaves. Some compensation for this kind of loss will occur in the case of low growing crops freely exposed to the sky; these condense the moisture of the air as dew, and a part of this falls to the ground.

The retention of rain on the leaves is, however, generally a point of minor importance; the principal loss of water occasioned by vegetation is due to the evaporation of water from the surface of the plant, chiefly through the stomata on the under side of the leaves. This transpiration of water by the plant is a part of its life-functions, and is indeed to a certain extent proportionate to the amount of growth; the larger is the crop, the greater being the amount of water evaporated by it (p. 52).

It is often supposed that a soil covered by a crop is moister than a bare soil; this may be true of the soil surface, which is thus shaded from the sun and protected from wind (p. 111), but it is not true of the soil as a whole[1]. The evaporation of water from the soil particles may be diminished by covering the land with a crop, but the evaporation through the leaves of the crop which takes its place is so much greater that the total evaporation is much increased. A crop in fact dries the soil through its roots, and the greatest part of

[1] The shading of forest soil is recognized as most important to its fertility, and apparently, to the storing of water in it. The influence of this continuous shading is indirect; it leads to the accumulation of a layer of humus upon the surface of the ground, which acts as a mulch, and also greatly favours the retention of water.

the water is thus removed from below the surface. A bare soil dries at its surface, and generally only to a slight depth, while a cropped soil dries from below, and often to a considerable depth.

The distribution of the roots has a great influence in determining the amount of water available to a crop, and the extent to which the soil is dried. Very deeply rooted crops, as lucerne and red clover, draw their supply from so great a depth of subsoil that they are practically independent of summer rains. Such is also the case with many forest trees. With such a crop as wheat, the extent of the development of the roots determines often the whole difference between a good and bad crop. The history of the Rothamsted wheat field shows that the best crops are obtained after a mild winter, followed by an early spring, especially when these seasons are rather dry. Under such circumstances the wheat finds itself in May provided with a maximum of root development, and it will then require little rain afterwards for its maturation. On the other hand, cold and wet weather during the early part of the plant's life prevents the development of the roots, and the crop consequently suffers in the first drought that occurs. Roots will not develop in a saturated soil: on heavy land, a dry spring goes far to ensure a good crop of corn.

Examples of the quantity of water consumed by crops have been already given (p. 51), and attention has been called to the fact that the capacity of a plant to evaporate water increases with the amount supplied. A good illustration of the drying effect of a cereal crop is afforded by the determinations of water in land growing barley, and in adjoining fallow ground, made at Rothamsted during the drought of

1870 (*Jour. Roy. Agri. Soc.* 1871, 121). The samples of soil were taken on June 27 and 28. About three-quarters of an inch of rain had fallen in the ten days preceding the taking of the samples.

TABLE XXI

WATER PER CENT. OF SOIL AFTER BARLEY AND AFTER FALLOW AT ROTHAMSTED

	Barley Land.	Fallow Land.	Excess in Fallow.
	per cent.	per cent.	per cent.
First 9 inches . . .	11.9	20.4	8.5
Second 9 inches . .	19.3	29.5	10.2
Third 9 inches . . .	22.8	34.8	12.0
Fourth 9 inches . .	25.1	34.3	9.2
Fifth 9 inches . . .	27.0	31.3	4.3

Lawes and Gilbert calculate that the barley crop had evaporated 909 tons of water per acre from fifty-four inches of soil, an amount almost exactly equal to nine inches of rain.

A comparison of the amount of evaporation from a bare soil, and from one covered with turf, is afforded by the results obtained in the different drain-gauges summarized in Table XXII. We have already referred to the amounts of evaporation from a water surface, from the surface of bare loam with flints, and from fine gravel. The results obtained by Greaves with a turfed sandy loam three feet deep, and by Evans with a turfed soil also three feet deep, show a greater evaporation in the whole year (18·1–20·0 inches) than that from the bare loam at Rothamsted (15·9–16·7 inches). This difference, however, by no means represents the full evaporating power of the grass turf. The average rainfall in the turf experiments was indeed much less than

that received at Rothamsted. The turf evaporates the whole of the summer rainfall, percolation only occurring in very heavy storms. In three summers during Sir John Evans' experiments, the rainfall in six months amounted to 15–16 inches; yet in two of these summers no percolation occurred through the turfed soil. The rainfall has thus been insufficient to show the full evaporating power of the turf. In the winter months, when a greater excess of water is available, the turf has evaporated considerably more than the water-surface.

TABLE XXII

EVAPORATION AND PERCOLATION UNDER VARIOUS CIRCUMSTANCES

	Rainfall per Annum.	Evaporation.			Percolation.		
		Summer, April–Sept.	Winter, Oct.–March.	Whole Year.	Summer, Apri.–Sept.	Winter, Oct.–March.	Whole Year.
	in.	in.	in.	in.	in.	in.	in.
Water Surface (Greaves)[1]	25·7	15·9	4·8	20·7			
Loam 20 inches (Lawes and Gilbert)[2] . . .	30·3	11·1	4·8	15·9	4·3	10·1	14·4
Loam 60 inches (Lawes and Gilbert)[2] . . .	30·3	11·5	5·2	16·7	3·9	9·7	13·6
Fine Gravel (Greaves)[1] .	25·7	3·0	1·2	4·2	9·1	12·4	21·5
Turfed Soil (Greaves)[1] .	25·7	11·4	6·7	18·1	0·7	6·9	7·6
Turfed Soil (Evans)[3] .	25·6	12·1	7·9	20·0	0·4	5·2	5·6

Another comparison of turf with bare soil is afforded by the results of the drain-gauges, three feet deep, established for four years, 1883–6, at the Experimental Station, Geneva, New York.

The rainfall in this case was again far too small to exhibit the evaporating power of the turf.

[1] Average of fourteen years. [2] Average of twenty years.
[3] Average of fifteen years.

TABLE XXIII

AVERAGE RESULTS DURING FOUR YEARS OF THE GENEVA (N.Y.) DRAIN-GAUGES

Rainfall.	Evaporation from		
	Turf.	Bare Soil.	Cultivated Soil.
inches.	inches.	inches.	inches.
25.0	21.2	17.4[1]	14.0[1]

In 1883 the evaporation from the turf reached 23·6 inches, out of a rainfall of twenty-four inches. The smallest evaporation in this experiment is from the cultivated soil, the surface of which was maintained in a loose condition, thus affording another illustration of the success of this plan for preserving soil water.

An additional illustration of the evaporating power of turf is furnished by the series of daily determinations of water in various soils conducted by the Agricultural Department of the United States in 1895 (*Soils, Bulletin* 2, 8). Towards the end of June the amount of water in the surface foot of a blue grass pasture varied between 9 and 10 per cent., while in similar soil with the sod removed it amounted to 19–20 per cent.

It follows from what has now been said, that when a soil is treated as a bare fallow, and left for a whole season without a crop, being submitted during that time to frequent ploughing, it is (notwithstanding its free exposure to sun and wind) in

[1] The *total* drainage from these gauges for 1886 is apparently wrongly stated on p. 348 of the *New York Fifth Report*. The figures for that year which are included above have been obtained by summing the monthly items on p. 347.

circumstances in which water will be stored up in the soil. This is indeed a fact, and the storing of water is to be reckoned among the benefits resulting from bare fallowing, a practice which is well known to be attended with most success in dry climates. King (*The Soil*, 191) determined on May 13 the percentage of water in two portions of a field about to be sown with maize; one portion had been previously a bare fallow, the other had carried clover. The results were as follows:—

Water per 100 of Dry Soil in Fallow and Clover Land

	Depth 1–6 inches.	Depth 12–18 inches.	Depth 18-24 inches.
Fallow	23.3	19.1	16.9
Clover Land ...	9.6	14.8	13.8

The maize sown on the fallow land would thus be far better able to withstand a summer drought, than the maize following clover.

The practice of planting so-called 'catch crops' immediately after harvest, and ploughing them in as green manure in spring, is a system full of advantage so far as the conservation of soil nitrogen is concerned; but King points out that in a dry climate such cropping and spring ploughing may be actually injurious, from the loss of soil water which they entail; and that in such a climate pains must be taken to plough in a green crop very early, as only then will it find sufficient moisture in the soil for its decomposition, and the tillage be accomplished without robbing the soil of water.

The injurious effect of weeds has a new light thrown upon it when we see that their growth dries the soil, and robs the crop of the water which it might have obtained. In the

Woburn Experimental Fruit Farm the ground surrounding certain young apple trees has been differently treated, in some cases grass has been sown round the tree, in other cases natural weeds have been allowed to accumulate, while in other cases the land has been kept clean throughout the summer by hoeing. The difference in the growth of these trees during the dry summer of 1896 was most marked, the trees standing in the bare soil worked with a hoe making an abundance of new wood, while hardly any growth took place in the case of the trees surrounded by vegetation. Weeds are far more injurious in a dry climate than in a wet.

The amount of evaporation from a soil largely affects the amount of percolation through it. In the case of ordinary permeable soils, the amount of rainfall and of evaporation determine the quantity of water which will pass through and appear as drainage. In Table XIV we see the influence of evaporation on percolation. In the winter, 70–80 per cent. of the rain comes through the drain-gauges at Rothamsted, while in summer only 20–27 per cent. passes through the soil. A great part of this summer drainage is derived from heavy storms, a portion of the water passing through the open channels in the soil before the body of the soil is saturated. The same quantity of rain in the form of light showers would produce no percolation.

In Table XIX we have seen striking illustrations of the fact that the annual evaporation from a bare soil is a fairly constant quantity, so that all rainfall over this amount appears as drainage. Doubling the rainfall has in fact increased the drainage five or six fold. If, however, land is covered with vegetation, the amount of evaporation ceases to be a constant quantity, every increase in rainfall up to an excessive amount

determining a greater growth, and a greater evaporation from the vegetation covering the surface. Thus the growth of forests tends greatly to diminish the volume of springs and rivers, and the destruction of forests is often followed by disastrous floods.

We have seen that on the bare soil at Rothamsted, active drainage commences in October, and lasts five months. In the wheat field at Rothamsted, a running of the drain-pipes is rare between March and September, owing to the drying of the land by the crop. The drain-pipes do not usually commence to run freely till November, and active drainage is limited to four months. With crops which cover the land in autumn and winter, drainage is reduced to a minimum. The farmer has thus the power, by suitable cropping, of greatly diminishing the autumn and winter drainage; this power is of great value, as the drainage water removes from the soil considerable quantities of plant food, especially calcium salts and nitrates.

Underground Water. The water which passes through the soil accumulates in the subsoil at very varying depths, forming a perfectly saturated stratum of soil or rock. The height of this saturated stratum varies with the character of the soil, and also with the rainfall and the season. When the height of this saturated stratum reaches a certain point, a discharge generally takes place in the form of springs, or as a general drainage from a wider area, into the river valleys, and finally into the sea. If no such discharge is possible, the soil becomes saturated to the surface, and a swamp is produced.

The position and behaviour of the underground water may be very much complicated by the presence of beds of impervious clay in the subsoil; the existence of such a bed determines at once the position of the underground water, which must

necessarily accumulate on its surface. The inclination of the clay bed determines also the direction in which natural drainage will occur.

When the complications of local clay beds are absent, the level of the underground water is found to follow generally the contour of the land surface, but in a less exaggerated manner, and with a decline in level in the direction of the drainage outfall. King points out that, as a result of this greater height of the water level under high ground, the land lying at the foot of hilly ground receives a continuous supply of underground water even in time of drought, amounting under favourable conditions to a veritable sub-irrigation.

When the distance of the stratum of saturated soil from the surface is considerable, this store of underground water is of no direct benefit to plants. We have already mentioned, that at Wisconsin a water level 6 ft. below the surface does not prevent the effects of drought being manifested by the crops, though doubtless they derive some benefit from the water. On the other hand, King tells us that the water level should not come nearer than 4 ft. to the surface if ordinary cereal crops are to be grown, as a higher water level prevents a proper development of the roots. With crops having short roots, as grass, the water level may with advantage be considerably higher. A water level may generally be lowered to any desired point by the insertion of drain pipes. The water level in a soil is raised by systems of irrigation.

The height of the water level in a soil varies considerably at different seasons of the year: this is best seen by measurement of the heights of water in wells. In deep wells in the chalk at Harpenden, Herts, the water is found at its lowest level in September, October or November. The rise commences at

various times, according to the preceding rainfall, and may occur in October, November, December, or, more rarely, in January. The greatest height is reached occasionally in February, but more generally in March or April, after which a decline sets in. The decline is slower than the rise. We have already seen that the commencement of large percolation through the soil is generally in October or November, and continues till the end of February; the rise and fall of the water in the wells thus follows, at a somewhat later date, the order of the percolation through the soil.

In Wisconsin, with a severe winter climate and a water level only a few feet below the surface, a great rise in the well water does not commence till April, after the spring thaw.

The alterations in the height of the underground water are considerable, extending to several feet; from three to five feet is the ordinary rise in the deep wells at Harpenden. It is at first sight puzzling that a few inches of autumn drainage should produce an increase of several feet in the height of the underground water. The explanation is however simple. The water in a soil, as we have already seen, merely occupies the interspaces between the particles. Supposing then the interspaces in a perfectly dry soil to amount to 40 per cent. of its volume, it is evident that four inches of rain would saturate ten inches of soil, and raise the level of the underground water to that extent. The effect produced in this direction is however really far greater, for the subsoil is not dry, but already holds a considerable amount of water; a small addition of drainage water thus suffices to complete the saturation of a considerable depth of subsoil.

Besides the considerable variations in the level of underground water determined by the season of the year, there are,

when the water level is near the surface, a great number of lesser variations. King, who has made an exhaustive study of the movements of water in shallow wells by means of a very exact self-registering apparatus (*Wisconsin 9th Rep.*, 129), tells us that the water level in such wells is in summer time never still, but always moving in one direction or the other. These movements in the water level are equally seen in the varying discharge of water by springs or by drain-pipes. They appear to be mainly occasioned by the expansion or contraction of the air imprisoned within the soil between the surface and the water-level. To a less extent, they are due to the alteration in the viscosity and surface tension of the water, brought about by changes in temperature. A rise in temperature starts a fresh percolation by diminishing the viscosity and surface tension of the water coating the soil particles, while a fall in temperature causes water to rise from the saturated soil into the unsaturated. The action due to the influence of temperature on the physical properties of water is thus in precisely the same direction as that due to the expansion or contraction of included air.

King found the discharge from a spring to be 8 per cent. greater with a falling than with a rising barometer, and the discharge from a drain-pipe diminished 15 per cent. for a rise of 0·1 inch in the barometer. The height of water recorded for the wells showed a regular daily fluctuation, the fall in level during the day being more or less made up by a rise in level during the night. The drain-pipes exhibited the same changes, the discharge reaching its maximum about 7 a.m. This diurnal variation is due to alterations in temperature; but the effect of the maximum daily temperature was not felt till early in the next morning, owing to the slow progress of

heat through the soil. A rising temperature and a falling barometer act in the same way; the air in the soil expands, and the water filling the interstices above the water level is expelled, and causes a rise in the water level of the soil. On the air again contracting, the water is reabsorbed by the soil, and the water level again falls.

King describes a blowing well in Wisconsin, in which the expansion and contraction of the underground air is manifested in a surprising manner. The water level is in this case at a considerable depth, and the soil between the surface and the water is chiefly gravel, which from its free drainage is of course largely filled with air. A falling barometer in this case produces so violent a draught of air out of the well as to blow a man's hat off; while with a rising barometer in winter time, the cold downward current is so severe as to freeze the pipes at a depth of 70 feet.

Wet and Dry Soils. The characters of dry and wet soils have been already fully described. The dry soils are those composed to a large extent of coarse particles, possessing a free percolation, and little power of retaining water. The wet soils are those composed of very fine particles, having an enormous extent of internal surface, and therefore retaining much water, and offering great resistance to the passage of water through them: the colloid constituents of clay or peat help greatly to intensify these properties.

The relation of soils to water is often much modified by the character of the subsoil. A sandy surface soil is agriculturally a very different thing when it has a subsoil of loam or clay, as the presence of this greatly increases the store of water at the disposal of the crop. On the other hand, a clay soil is no longer called wet when it has a subsoil of chalk to remove

superfluous water. The character of any soil will also be much affected by its position, whether on a hill side, or in a valley receiving the drainage of higher land. The height of the water level in the subsoil is also another condition which may entirely alter the agricultural character of the land.

The most suitable character for a soil must depend on the characters of the climate and situation in which it is placed, and the crops it is desired to grow; properties of the greatest value under one set of conditions, may be those producing most evil under contrary circumstances. A coarse sand may be a very poor soil under arable culture, but it would answer admirably for sewage irrigation, and would also in time produce a good pine forest. Well supplied with manure it might make excellent early market-garden land. A clay that could only be laid down in grass with an annual rainfall of forty inches, might be used with great advantage for arable culture where the rainfall is only twenty-five inches. A marsh which would be useless in England, would in India produce luxuriant crops of rice. The kind of agriculture which can be most usefully adopted must indeed always depend on the special conditions of the locality. In the climate of England, the soils yielding the most favourable supply of water for arable culture are loams, alluvial silts, and very fine sands containing some humus; such soils are capable when deep of storing much water, while at the same time they allow of a free movement of water within them, and drain sufficiently speedily to favour a large development of root.

Amelioration of the Physical Properties of Soil. Although the natural conditions of soil and climate have always a

preponderating influence in determining the agricultural value of land, considerable improvements in the character of the soil may often be effected by artificial means, if we bear in mind the facts laid down in the preceding pages. As the same causes, and the same modes of cure, apply as a rule both to cases of deficiency and excess of water supply, and to cases of deficiency and excess in the tenacity of the soil, we shall most conveniently consider these subjects together.

In a coarse sand we have a soil of minimum tenacity, and also one of minimum capacity for retaining water. The evils due to lack of tenacity are exemplified in the case of blowing sands. When these sands are in a bare dry condition, the wind separates the finer and more valuable particles, and then rolls over the coarser grains, which may thus be carried in great drifts to considerable distances, rendering much land infertile. If such land can be permanently covered with vegetation, the mischief we have described will be of course prevented. Where a coarse sand is found naturally covered by a pine forest, it will be a great mistake to cut down the forest and attempt arable culture. The establishment of perennial plants having widely spread roots is a first step in the reclamation of blowing sands. Shelter from wind must also be provided. Fences will check the progress of sand in the same way as the groins on the seashore hinder the movement of the shingle.

King has investigated the question of the agricultural treatment of the blowing sands of Wisconsin (*Wisconsin 11th Rep.*, 292). He points out the great diminution in the velocity of the wind which results even from shelters of small height above the ground. Land left ploughed in ridges across the prevailing direction of the wind was little injured when a

level soil had been badly disturbed by the wind. The shelter afforded by low-growing crops was considerable; and he makes the very practical suggestion that such land should be always cultivated in strips, fifteen or twenty rods wide, grass or clover alternating with the arable culture.

Both the tenacity and the water-holding power of coarse sandy soils may be greatly improved by a small admixture with clay; this plan admits of being carried out with economical success when the clay is found in the subsoil of the field, or in the immediate neighbourhood. The application of marl (a calcareous clay) to light soils is a common practice in the eastern counties of England; from forty to sixty tons per acre are usually applied. The effect of this dressing is seen for many years.

Peaty and fen land are also much benefited by the addition of clay, which increases the weight and coherence of the surface soil. On Rimpau's system for reclaiming peat land, trenches are cut at intervals across the peat down to the clay bottom which always underlies it; the clay is then brought up and spread on the surrounding peat, the land being thus drained and clayed at the same time. A similar plan is made use of in the Lincolnshire fens; the trenches are in this case eight to ten yards apart.

Another very practical mode of improving the coherence and water-holding power of sandy soils is by increasing the proportion of humus. For garden purposes, or on a small scale, this may be done by digging or ploughing in heavy dressings of well-rotted farmyard manure. On a large scale, the same result may be accomplished by the ploughing in of green crops, which on their decay add greatly to the store of humus in the soil. Preference is usually given to legumi-

nous crops for this purpose, as the soil is then enriched with nitrogen from the atmosphere. Lupins are commonly employed in Germany for the amelioration of sandy soil.

The water-holding power of a sandy soil is increased by keeping it consolidated; the treading of sheep in winter time is thus beneficial. In a light soil, crops should be planted as early as possible, so that the fullest root development may be attained before summer begins. As soon as the season for evaporation commences the surface of the soil should receive a shallow cultivation, and a layer of loose earth should be maintained on the surface throughout the summer. In the garden, mulching is a still more effective plan for preserving soil water. The temporary increase of water at the surface obtained by rolling the soil has been already mentioned.

We turn now to the opposite case of a clay soil, exhibiting an excessive tenacity, hindering both root development and the production of tilth; retaining an injurious amount of water after rain, and drying in summer time into a hard mass. We seek in this case to diminish the coherence of the soil, to make it more friable and more permeable to water. With very stiff clay soils it may be impossible to remedy the evils which they present in an economical manner, in which case the land is allowed to remain permanently in grass. When in grass, the clay soil becomes of great value; the excessive supply of water near the surface is then an advantage, while under the protection of a sod a fairly good natural tilth is finally obtained. In the case of clay soils of a less extreme character a very considerable amount of improvement is practicable.

Deep autumn ploughing, and exposure of the ridged surface to winter frosts, is a method of first-class importance for

improving the condition of the surface soil, and obtaining a good tilth in spring. If a subsoiler follows the plough in the furrows, and penetrates and stirs the subsoil without inverting it, still more benefit will be obtained. By such deep tillage, the permeability of the surface soil is much increased, and rain passes through freely to the subsoil. The improvements effected by frost and tillage are not however very permanent; every storm of rain tends to bring the clay back to its original condition.

For practical purposes it is useless to attempt to improve the texture of a stiff clay by admixture with sand, the effect produced being far too small to render the measure economical. Clay-burning is a more practical scheme; it may be seen frequently in operation in railway cuttings where it is desired to prevent the erosion of the banks by storm water. In the field, the dried clods of soil are made into heaps with hedge cuttings, or other combustible matter, and slowly burnt at a low temperature. The burnt clay is then spread over the land and turned in with the plough. Sixty to eighty cubic yards of burnt clay per acre is a usual dressing. It should be recollected that the nitrogenous matter in the soil is lost by burning; the potash in the clay becomes, however, more soluble by this treatment, if the burning has not been conducted at too high a temperature, and especially if the clay contains some lime. Clay-burning is to be regarded as an extreme measure, to be adopted only when ordinary methods have not proved sufficiently efficacious.

A method far more frequently adopted is the application of chalk or lime to the clay. The action of lime is peculiar. We have already seen (p. 31) that it brings about the coagulation of the colloid clay, and completely alters its physical character.

The soils containing the smallest proportion of true colloid clay are those most successfully treated by lime. The action of the lime extends to a considerable depth, and endures for some time; it is not, however, strictly permanent, as lime is continually being removed from the soil in the drainage water. It is usual to apply ten to fifteen tons of chalk, or three to nine tons of lime per acre. The land is best ploughed and then limed in autumn, and afterwards harrowed in the spring.

The enrichment of a clay soil with humus very much improves its physical condition, and for garden purposes there is no better treatment for a clay soil than the digging in of large quantities of fresh stable manure. In the field, great advantage is experienced by growing clover and grass for several years, and then ploughing in the crop residues remaining in the surface soil.

The methods we have mentioned serve chiefly to ameliorate the surface soil. If a deep clay soil is to be permanently improved it is generally necessary to have recourse at the same time to draining. The primitive methods of draining consisted in throwing the land by the plough into high ridges or 'lands,' or in cutting ditches; the far more effective modern drainage systems are carried out by the insertion of drain-pipes in the subsoil, the water collected by these pipes being removed by a main drain into which they deliver.

There are two very distinct cases in which draining is a remedy. If the surface soil is freely permeable to water, but a bed of clay occurs in the subsoil, the water collects upon the surface of this clay, and may rise to such a height as will injure the fertility of the land. To remove this water it is only necessary to tap the water reservoir above the clay bed at such a distance below the surface as will prevent the water

standing at an injurious height. A few pipes generally suffice for this work, and the effect they produce is immediate[1].

The second case is that of a deep clay. Here there is no water reservoir to be tapped; the whole soil is equally full of water, and holds it firmly. Drain-pipes are usually laid in such a soil, 15–20 ft. apart, and 3 ft. below the surface. Little or no water is at first delivered by the pipes, and no improvement in the soil may be perceived for some time, the effect being very gradual. The amelioration consists first and chiefly in an alteration in the physical character of the clay, which commences round the pipe and gradually extends from it. The clay subsoil, being opened up by the introduction of pipes, is in fact placed under the influence of the changes of temperature and changes in the condition of dryness, which we have already seen determine the gradual disintegration of a tenacious soil, and the formation of a looser texture. The forces thus brought to bear upon the subsoil are far weaker than those which ordinarily affect the surface; but, on the other hand, the transformation in the subsoil is not hindered by the occurrence of tillage operations, or by the puddling effect of heavy rain. As this change in the texture of the clay proceeds, the soil is able to part more freely with its excess of water, and the drying thus effected serves to extend still further the alteration in the character of the clay. Drainage operations will be especially successful when lime is at the same time applied to the surface.

[1] If the impervious layer is quite near the surface, and is of the nature of a 'pan' (see pp. 28, 29, 46), the most effectual remedy will be the destruction of this pan by a subsoil plough. Steam cultivation is in such cases of special value. In parts of the United States it has been found practicable to shatter the pan, and thus ensure the drainage of the surface soil, by means of dynamite cartridges.

It may naturally be thought that crops on a drained elay will suffer more in a season of drought than those on an undrained clay, the quantity of water held near the surface being undoubtedly greater in the latter case. This is not so, indeed the reverse is found to be the fact. The roots of the crop are indeed far more widely distributed in the drained soil, and are thus far better able to obtain water. Moreover, the movement of water is more speedy in a drained than in an undrained soil.

CHAPTER IV

RELATIONS OF SOIL TO HEAT

Influence of Temperature on Life—Sources of Soil Heat—Influence of Latitude and Aspect—Temperature of Surface Soil—Specific Heat of Soils—Conductivity of Soil Constituents—Radiation of Heat—Influence of Water on Soil Temperature—Temperature of Subsoil—Prevention of Summer Frost.

Influence of Temperature on Life. All the processes of life, whether in plants or animals, are only possible between certain limits of temperature, below or above which life cannot exist. Each kind of life has a range of temperature more or less peculiar to itself, within which its functions may possibly be performed; it has also an optimum temperature at which the greatest amount of vigour is exhibited; this optimum temperature may be different in different stages of growth. All living beings have, however, some power of adaptation to the circumstances in which they are placed.

The life processes which occur in the soil are distinctly affected by the temperature of the soil; the germination of seeds is one of the processes so affected. The seeds of some plants, as rye, mustard, and lucerne, may undergo a very slow germination at the freezing point, but for most seeds a higher temperature is required. F. Haberlandt (*Landw. Versuchs-Stationen*, xvii. 104) experimented with a great variety of seeds at four temperatures; the lowest temperatures at which germination took place were as follows:—

Lowest Temperatures for Germination

Wheat, Barley, Oats, Rye, Buckwheat, Rye Grass, Peas, Beans, Vetches, Lupins, Red Clover, Lucerne, Mustard, Rape, Turnip, Beet, Hemp, Flax	32° - 40° F.
Maize, Sorghum, Timothy Grass, Sanfoin, Carrot, Sunflower	40° - 51° F.
Tomato, Tobacco, Pumpkin	51° - 60° F.
Cucumber, Melon	60° - 65° F.

The time required to produce germination becomes shorter as the temperature rises, until the optimum temperature is passed. Haberlandt's results were as follows :—

Days required for first appearance of Radicle at various Temperatures

	40°	51°	60°	65° F.
Rye	4	2½	1	1
Wheat and Barley	6	3	2	1¾
Oats	7	3¾	2¾	2
Rye Grass	10	5½	3¾	3
Peas	5	3	1¾	1¾
Vetches	6	5	2	2
Lucerne	6	3¾	2¾	2
Red Clover	7½	3	1¾	1
Beans	7	6½	4¾	4¼
Mustard	2	1½	1	¾
Rape	6	2	1	1
Turnip	8	4	2	1¾
Sugar-beet	22	9	3¾	3¾
Flax	8	4½	2	2
Timothy Grass	...	6½	3¼	3
Maize	...	11¼	3¼	3
Carrot	...	6¾	4¼	3¼
Sanfoin	...	7¼	3½	3
Sunflower	...	25	3	2
Tomato	...	...	6	3¼
Tobacco	...	...	9	6¼
Pumpkin	...	...	10¾	4

The temperature at which germination was most speedy, and the largest proportion of seeds germinated (optimum

temperature), and the highest temperature at which germination was possible, were approximately ascertained by Haberlandt by experiments at 61°, 77°, 88°, 100°, 111°, 122° F.

Optimum and Maximum Temperatures for Germination

	Optimum Temperature.		*Maximum Temperature.*
Barley, Vetches	61° - 77°	...	88° - 100°
Mustard	61° - 88°	...	88° - 100°
Rye, Wheat, Oats, Timothy Grass, Beans, Carrot, Flax, Tobacco	77°	...	88° - 100°
Turnips	77° - 88°	...	88° - 100°
Buckwheat	77° - 88°	...	100° - 111°
Red Clover, Lucerne	77° - 100°	...	100° - 111°
Sorghum	77° - 100°	...	111° - 122°
Rye Grass	88°	...	88° - 100°
Lupins, Sunflower	88°	...	100° - 111°
Cucumber	88°	...	111° - 122°
Maize, Melon	88° - 100°	...	111° - 122°
Rape	100°	...	100° - 111°
Pumpkin	100°	...	111° - 122°

These results afford ample illustrations of the dependence of germination on the temperature of the soil. The warmer the soil is, the quicker will the seed germinate, and the earlier will be the ensuing crop. A warm soil in spring time is thus of immense advantage to the agriculturist.

The temperature of the soil has an equally great influence on the subsequent development of the plant. Bialoblocki (*Landw. Versuchs-Stationen*, xiii. 424) grew barley in pots of sand maintained at various temperatures. The sand was watered with a solution of nutritive salts, the influence of heat on the chemical changes proceeding in a natural soil was thus eliminated. In the first series of experiments, the pots were maintained at their respective temperatures from the time when the seeds of barley were sown. In the second

series the barley plants were allowed to develop for two months at the temperature of the air before the temperatures of the soils were altered; in consequence of this change in the method, the ill effect of the higher temperatures is less apparent in this series than in the first.

TABLE XXIV

INFLUENCE OF SOIL TEMPERATURE ON THE YIELD OF BARLEY

Temperature of Soil.	Dry Matter in Final Produce.	
	Series I.	Series II.
	grams.	grams.
10° C. or 50° F.	7·64	7.33
20° ,, ,, 68° ,,	8·22	9.15
30° ,, ,, 86° ,,	3·85	5.33
40° ,, ,, 104° ,,	0·93	3.47

A soil temperature of 50° F. was apparently sufficient for the normal development of the barley plant, but the ripening of the crop was slow, and none of the corn was more than milk-ripe when the experiment concluded. The soil temperature of 68° gave a larger produce and better ripened ears. With much higher soil temperatures the amount of produce was much reduced.

In an experiment lasting only twenty days, it appeared that the optimum soil temperature for wheat was somewhat higher than that for barley, and this again somewhat higher than that required by rye.

The great influence of soil temperature on plant growth is well known to gardeners, who frequently employ hot-beds, and make use of a bottom heat for striking cuttings and

other purposes. In extreme northern latitudes the low temperature of the soil limits both the kind of crops which can be grown, and the amount of produce obtained. The much greater length of day in summer time does not compensate for the deficiency of soil temperature.

Besides the direct influence of the temperature of the soil on the growth of crops, it has a very considerable influence on the activity of the lower forms of life with which a fertile soil abounds. The dead organic matter of the soil, the remains of vegetable and animal tissue, is made again available as plant food by the successive action of various kinds of fungi and bacteria. The production of nitrates in the soil, a process having a most intimate connexion with its fertility, is, for instance, brought about by the successive action of several species of bacteria. The activity of these living agents is entirely dependent on the temperature of the soil in which they live. At the freezing point their action is practically nil; it increases as the temperature rises till the optimum temperature is passed, when a rapid decline sets in. Vital action seldom continues beyond 50° C. The soil temperature most favourable to the chemical activity of bacteria varies with different species; it generally lies between 30° and 40° C.

The temperature of the soil also affects the physical processes occurring in it. We have already noticed (pp. 87, 129) the great influence of temperature on the movements of water and air within the soil. Temperature also affects the movements of salts (p. 193). Indeed, there is probably no physical process within the soil which is not affected by temperature.

The chemical processes within the soil are equally influenced by temperature. The chemical changes in dead matter which

occur without the intervention of living organisms are in fact confined to certain limits of temperature, and are promoted or retarded as the temperature approaches or recedes from the optimum point, in a similar manner, though within far wider limits, as we have already seen happens in the case of the chemical changes produced by the agency of life.

Thus, speaking generally, the whole of the processes within the soil become more active as the temperature rises. Winter is a time of sleep, summer is a time of activity. The productive power of a soil depends largely on its temperature.

Sources of Soil Heat. The surface of a globe moving alone in space must very shortly reach a condition of intense cold. The present temperature of the surface of our earth is almost entirely maintained by the radiation received from the sun. To a very small extent the temperature of the soil will be due to the heat evolved in chemical and physical actions; this heat is, however, in most cases merely a reappearance of solar energy previously consumed in the production of chemical or physical work, which afterwards, by a reverse action, is resolved into its original elements. To a small extent, the temperature of the surface of the earth is also raised by the gradual outward passage of internal heat.

The great internal heat of the earth is a familiar fact, shown by the rise of temperature in the rocks when mines are sunk into the earth, and also by volcanic phenomena. The rate of increase in temperature on sinking below the surface is not uniform in every place. If we assume as an average a rise of 1° F. for each 50 or 60 feet of descent, we shall have a temperature equal to that of boiling water at about a mile and a half below the surface. It is impossible to say

to what extent the temperature of the surface soil is affected by the internal heat of the earth. The average temperature of the surface soil is in England about 1° F. higher than the temperature of the air above the surface, and the average temperature of the subsoil becomes slowly higher as we descend. Since, however, the air at the surface of the earth derives almost the whole of its heat from contact with the earth, and is itself cooled by mixture with the air of the upper regions of the atmosphere, the surface of the earth should be a little warmer than the air even if the whole of its heat was derived from solar radiation. The heat derived from the interior of the earth will be equally distributed through all the seasons of the year; it will probably differ in amount in different places, owing to the greater or less thickness and conductivity of the earth's crust.

We have already seen, p. 62, that a thoroughly dried soil rises somewhat in temperature when moistened, especially if it is rich in colloid constituents. A still greater rise in temperature is observed when a soil condenses water from the air.

Under special circumstances, considerable quantities of heat may be generated by chemical action. It has been well said that when a log of wood decays in the forest it produces as much heat as when burnt in a furnace. If the products—water and carbonic acid—are the same under both conditions, the heat produced must also be the same. The heat evolved is, however, in one case spread over many years, and in the other case is probably concentrated into one hour. The rise of temperature is thus in the first instance imperceptible, and in the latter very great; the total quantity of heat being the same in each case.

If in place of a log of wood we deal with some vegetable matter which more easily undergoes chemical change, the rise of temperature during fermentation and decay may become very perceptible; we have an excellent example of this in the case of the heating of a damp hayrick or of a silo. For the evolution of heat it is by no means essential that oxidation to water and carbonic acid should take place. An extreme oxidation, having these final products, will indeed produce the whole of the heat which the fuel substance is capable of yielding; but heat is also produced by fermentative changes in which oxidation plays an insignificant part. In the alcoholic fermentation of sugar, by far the greatest part of the sugar is simply split up into two bodies, alcohol and carbonic acid, no oxidation of the sugar occurring, and the action taking place in the absence of air, yet the production of heat is well marked throughout the whole operation. The evolution of heat in the stack, the silo, and the hot-bed, is generally the result of fermentive changes. Only a portion of the stable manure or hay is capable of rapid fermentation; the active production of heat thus soon ceases, and the subsequent changes become very slow, if a secondary action does not occur leading to ignition.

Nearly the whole of the processes bringing about the natural destruction of organic matter, within the soil or out of it, and whether by means of fermentation or oxidation, are the work of living organisms—animals, fungi, yeasts, bacteria; that this is the case is proved by these actions ceasing when the organisms present have been destroyed. As these agents can only work within certain limits of temperature, a rise of temperature beyond a certain point destroys the agent, and brings the work to an end. Thus

it is well known that sweet silage is produced by allowing the mass of green matter to heat in the first place to a temperature at which the bacteria producing lactic acid are destroyed, and then checking the action. Both in the silo and in the hot-bed it is however quite easy to obtain temperatures considerably exceeding those at which most organisms perish. It is now known that a special class of bacteria exists in the surface soil, and is probably widely distributed, which is capable of living and performing energetic work, at temperatures distinctly exceeding 70° C. (158° F.[1]). These bacteria doubtless take an active share in the chemical changes producing heat both in the hot-bed and in the silo.

Dybowski (*Annales agronomiques*, 1887, 268) has made careful experiments on the course of the development of heat in hot-beds containing a 2 ft. layer of various materials. The highest temperature, 75° C., was obtained from horse manure; the lowest, 37° C., from a mass of mixed dead leaves. For the maximum heat to be obtained the material must be in a fresh state.

Cases sometimes arise in which the actual ignition of a haystack or manure heap occurs. The rise of temperature above 75° is clearly the result of chemical oxidation, carried on without the aid of living organisms. We must assume that fermentation has produced substances which at the temperature of the rick are rapidly oxidized if air can obtain access, and that the production of heat is thus carried to the point of actual combustion.

[1] These high-temperature bacteria are readily separated from the other organisms in soil by inoculating with soil tubes of broth maintained at 65° C. Under these circumstances only the high-temperature organisms will develop.

Although farmyard manure furnishes a considerable source of heat when employed in a hot-bed, its application has little influence on the temperature of farm soils. This is chiefly owing to the small proportion of farmyard manure which is mixed with the soil. The farmer also seldom applies the manure in a fresh state; a portion of its heat-producing power is thus lost before it reaches the land.

A few experiments were made by Georgeson at the Imperial College at Tokio (*Agricultural Science*, i. 251) on the alteration in temperature which followed the application of various quantities of farmyard manure to the soil. The soil used was peculiarly light and porous, being in fact a volcanic ash. The manure was partly decayed, but still rather long. The soil and manure were well mixed, and wooden frames were filled with the mixture to a depth of 1 ft.; one frame received no manure. The frames were sunk in the open ground, the top of each frame being level with the surface. The experimental soils were thus under perfectly natural conditions in respect to rainfall, drainage, &c. The average temperatures of the soils, in successive five-day periods, are shown in Table XXV. The temperatures are given in Fahrenheit's degrees.

The increase in temperature was greatest during the first five days, and then rapidly diminished. After the first fifteen days the increase became almost imperceptible where only ten tons of manure per acre had been applied, but continued to be distinct after twenty-five days when forty and eighty tons of manure had been employed. As an ordinary dressing of farmyard manure does not exceed ten tons per acre, and a very liberal dressing seldom exceeds twenty tons per acre, it would appear that the rise of temperature pro-

duced in the soil is not great, and soon ceases; it may, however, have a distinct effect in hastening the germination of seeds, and must aid in protecting a spring-sown crop from the effects of frost. The deficiency in temperature observed in the last five days of the experiment in the case of the soils receiving the smallest dressings of manure is attributed by Georgeson to the cooling effect of the larger amount of water held by the manured soils (see p. 72). As the result of adding farmyard manure to a soil is in nearly every case to increase the amount of water retained near the surface, it would appear that the after effect of the manure is rather to cool than to warm the land.

Table XXV

INFLUENCE OF FARMYARD MANURE ON TEMPERATURE OF SOIL

	Farmyard Manure per acre.				
	None.	10 tons.	20 tons.	40 tons.	80 tons.
Temperature, Oct. 27–31 .	60°.5	62°.5	63°.8	63°.1	65°.1
Excess over unmanured .	...	2°.0	3°.3	2°.6	4°.6
Temperature, Nov. 1–5 . .	58°.5	59°.5	60°.2	61°.3	62°.2
Excess over unmanured .	...	1°.0	1°.7	2°.8	3°.7
Temperature, Nov. 6–10 . .	57°.2	57°.8	58°.4	59°.3	60°.4
Excess over unmanured .	...	0°.6	1°.2	2°.1	3°.2
Temperature, Nov. 11–15 .	54°.7	54°.8	55°.3	56°.2	56°.8
Excess over unmanured .	...	0°.1	0°.6	1°.5	2°.1
Temperature, Nov. 16–22 .	50°.8	49°.8	50°.1	51°.6	52°.5
Difference from manuring	...	–1°.0	–0°.7	0°.8	1°.7
Average excess with manure in 1st twenty days.		0°.93	1°.70	2°.25	3°.40

Experiments by F. Wagner on the same subject (Wollny, *Forsch. der Agrikulturphysik*, v. 373) showed that with the heaviest dressing of farmyard manure, about twenty tons per acre, the temperature of the soil remained above that of the unmanured land for four to twelve weeks. The greatest excess of temperature observed was 5° F., but the highest average excess of temperature was 1° F. Generally the average excess of temperature by manuring was from 0°·2–0°·7.

The ploughing in of green crops has a similar effect on the temperature of the soil as the application of farmyard manure. The after result of such organic manuring is to somewhat lower the temperature of the soil, probably for the reason already stated.

For the greatest rise in temperature to occur, a soil must be porous, and moist, and of a temperature not below 50° F.; the rise is in fact greatest in summer time, all processes of fermentation and oxidation being then most vigorous.

As tillage greatly promotes oxidation, the cultivation of a soil in spring, especially if it contains vegetable residues, (as for instance a clover ley), will tend to increase its temperature.

We have seen that neither the internal heat of the earth, nor the chemical and physical changes which occur in the soil, have any considerable effect on the temperature of the earth's surface; this depends almost entirely on the amount of radiant energy received from the sun.

The amount of heat received from the sun depends of course primarily on the activity of solar processes, which may apparently vary from time to time. The great alterations in climate in the past history of our globe are difficult

to explain without assuming a difference in the amount of heat received from the sun. It is now generally assumed that the solar energy is greatest during the period of most numerous sun spots, which returns about every eleven years.

The heat received from the sun by any portion of the earth's surface depends greatly on the transparency of the atmosphere; our cold and hot summers are chiefly determined by the presence or absence of cloud. For the greatest amount of heat to reach the earth the air must not only be clear, but also dry. Dry air has but little power of absorbing the heat rays from the sun, but water-vapour is an active absorbent. It is thus in elevated regions, having a clear dry atmosphere, that the heating power of the sun is most strongly felt. The highest temperature shown each month during the winter of 1870–1 by a blackened thermometer in vacuo at Greenwich, and at Davos in Switzerland, 5,400 ft. above the sea, was as follows:—

	Greenwich.	*Davos.*
November	95°·2	115°·3
December	78°·8	115°·0
January	79°·9	117°·1
February	101°·8	126°·0

The sun's rays were thus far hotter at Davos than at Greenwich, although the ground at Davos was continuously covered by snow.

Although cloud, and to a less extent a moist atmosphere, greatly hinder the sun's heat from reaching the earth, they do in an equal degree prevent a loss of heat from the earth. The condition of clear sky and dry air which admits a free passage to the sun's radiation during the day, allows an equally free radiation from the earth during the night; a climate of great extremes of temperature, of hot days and

cold nights is thus produced. With the cloudy sky, and moist air, which characterize the climate of an island, the extremes just mentioned are never found, but the climate is remarkably uniform in temperature. The same conditions of sky which give us a cool summer produce also a mild winter.

Influence of Latitude and Aspect. The angle at which the sun's rays strike the earth has a very important influence upon their heating effect at the earth's surface. Every flat portion of the earth's surface receives the same number of

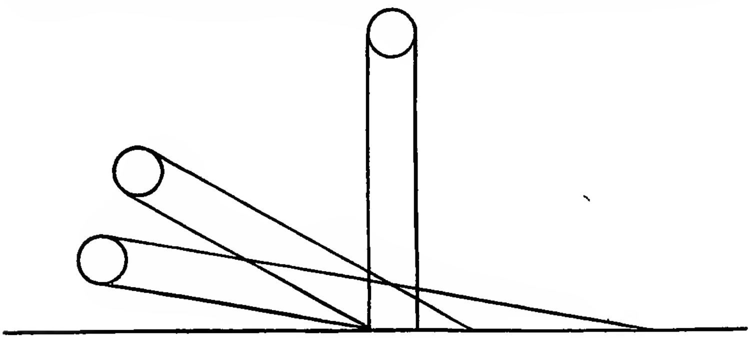

FIGURE 4.

hours of sunshine in the course of the year, and at the spring and autumnal equinox the day and night are of equal length over the whole globe; yet how extremely different is the temperature in the tropics and in the arctic regions! The enormous influence of latitude on climate is simply due to the varying angle at which the sun's rays reach the earth The simplest illustration is however furnished by an ordinary summer's day. How different is the intensity of the sun's rays at sunrise or at sunset, when the sun is near the horizon, to what it is at noon, when the sun has risen to a great height! This difference in the intensity of the sun's heat

is simply due to the different angle at which the rays fall on the earth at different times of the day.

The reason why so much depends on the angle at which the sun's rays strike the earth will appear by an inspection of Figure 4. Here three sunbeams of equal dimensions are represented as falling on a flat surface, one vertically, another at an angle of 30°, and the third at an angle of 10°. It will be seen that the beam at 30° spreads itself over twice as

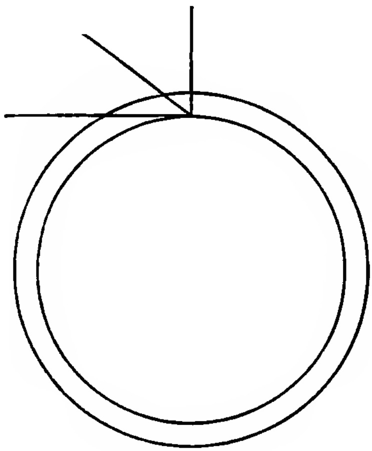

FIGURE 5.

much earth surface as the vertical beam, and consequently only supplies half the heat per unit of area; while the beam at 10° spreads itself over more than five times the surface, and thus supplies less than one-fifth of the heat per unit of area which the same beam would furnish if falling vertically.

Another cause, but one far less important, of the diminishing heating power of the sun's rays as it approaches the horizon, is the greater atmospheric absorption of heat rays which then takes place. In Figure 5 we have a representation of an

atmosphere surrounding a globe. It is at once evident that the vertical rays falling on the globe pass through a thinner stratum of air than the rays falling on the same point from a smaller angle, the maximum amount of atmospheric interference occurring plainly at sunrise and sunset.

The facts we have just brought forward not only elucidate the influence of latitude on climate, they also help to explain the well-known effect of aspect on the fertility of land. In

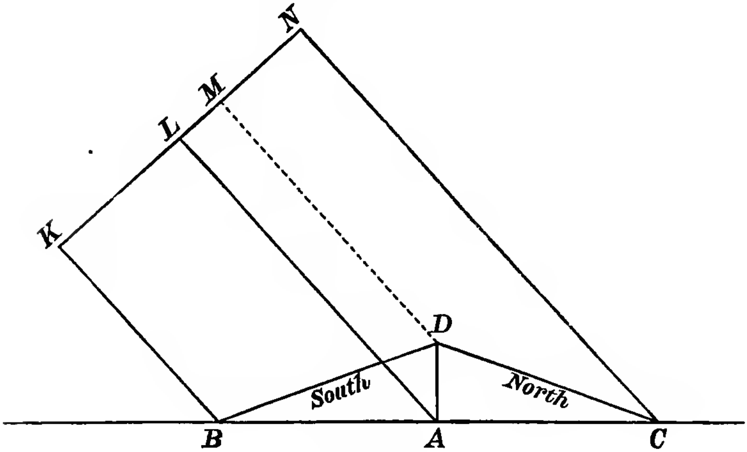

FIGURE 6.

our northern hemisphere a field or garden facing or sloping towards the south will for most purposes be greatly preferred to one sloping towards the north, and will yield much earlier crops. The inclination towards the south does indeed in part counteract the prejudicial effect of north latitude, and causes the sun's rays to fall at a higher angle upon the surface.

In Figure 6 we have a flat surface *BC*, divided into two equal portions *AB* and *AC*, and receiving equal solar radia-

tion represented by the beams *KL* and *LN*. If now we replace this flat surface by a hill having a slope of 20°, facing south and north, it is at once evident that the equality of the radiation on the two portions is destroyed, and that, with the sun at the angle assumed, the southern slope will now receive twice as much heat as the northern.

The greater heat obtained from the sun on a southern slope is, of course, received only in the daytime, and when the sky is clear. The increase of heat is confined to the *surface of the ground*, which becomes sensibly warmer; the vegetation upon it does not obtain any increased radiation from the sun, (though it will from the ground), the growth of plants being always perpendicular, whatever the slope of the soil. The general temperature of the air is also unaffected by the inclination of the ground, except near the surface during the hours of sunshine. In addition to the increased intensity of solar radiation, the southern slope has also the advantage over the northern of more hours of sunshine, and of protection from cold winds. As the southern slope gains heat only during sunshine, and falls at other times to the general temperature, it follows that the extreme range of temperature is greatest with a southern aspect.

Wollny (*Forsch. der Agrikulturphysik*, i. 263) determined the temperature of the soil at 6 inches below the surface on various sides of artificial hills of sandy soil containing humus. The experiment was made at Munich, and extended throughout a whole year. When the slope of the hill was 15°, the average temperature of the south side was 1°·5 F. more than that of the north. When the slope was 30°, the average excess of temperature on the south side was 3°·1 F. From May to August the south-east side was the warmest; in September

and October the south side; from November to April the south-west. A south-east aspect is the one generally preferred by gardeners, as the sunshine in this case begins at an earlier hour. Such an aspect may, however, be attended with disadvantage in the case of spring frosts, owing to the too rapid thawing of the vegetation.

King (*The Soil*, 228) determined the temperature of a red clay soil on the south shore of Lake Superior on July 31, both where the slope was 18° and on the level. The results were as follows:—

	First foot.	*Second foot.*	*Third foot.*
South Slope	70°.3 ...	68°.1 ...	66°.4 F.
Level	67°.2 ...	65°.4 ...	63°.6 ,,
Excess on South	3°.1 ...	2°.7 ...	2°.8

Thus, in the middle of summer, the greater heat on the south side had penetrated to a considerable depth.

When planting in rows or ridges the exposure to the sun should always be considered. Rows running north and south will be equally exposed to the sun on both sides, while those running east and west will, in the case of tall plants, receive but little sunshine on their northern side.

Temperature of Surface Soil. In the case of a bare dry soil, freely exposed to the sky, the range of temperature at the surface is very great, far greater than that of the air above it. The maximum temperature reached by such a soil is chiefly determined by the intensity of the solar radiation which it receives. Sir J. F. W. Herschel sunk a thermometer 4 inches deep in the sand in South Africa, and observed the temperature rise to 159° F. Schübler (*Jour. Roy. Agri. Soc.* 1840, i. 206) determined during two years the temperature of the garden mould on the south side of his

house at Tübingen in Germany, between noon and one o'clock, on every day when the weather was perfectly fine; the bulb of the thermometer was placed one-twelfth of an inch beneath the surface. The highest temperature thus observed was 153°·5 F., the temperature of the air at the same time being 78°. The average of the temperatures recorded for each month of the year, with the average temperatures of the air in the shade taken at the same time, will be found in Table XXVI. In the same table will be found the average midday temperatures observed by Schübler at Geneva during a single year; in this case, however, the temperatures were observed every day, and not only in fine weather.

Table XXVI

MEAN TEMPERATURES OF SOIL AND AIR AT MIDDAY (SCHÜBLER)

	In Fine Weather, Tübingen.			In Variable Weather, Geneva.		
	Surface Soil.	Air in Shade.	Soil in excess of Air.	Surface Soil.	Three inches deep.	Air in Shade.
January . . .	54°·1	24°·6	29°·5	43°·0	38°·5	38°·2
February . .	86°·2	43°·0	43°·2	45°·7	39°·8	36°·8
March . . .	99°·5	46°·6	52°·9	53°·2	43°·2	38°·1
April	121°·6	61°·7	59°·9	78°·9	60°·7	50°·1
May	131°·2	67°·3	63°·9	80°·1	64°·4	55°·9
June	139°·8	75°·2	64°·6	89°·1	73°·6	60°·9
July	146°·3	81°·3	65°·0	93°·4	73°·3	63°·2
August . . .	130°·1	68°·9	61°·2	96°·0	76°·9	65°·8
September . .	119°·8	68°·0	51°·8	82°·8	70°·2	62°·4
October . . .	80°·8	42°·8	38°·0	59°·8	54°·4	51°·8
November . .	72°·7	40°·1	32°·6	47°·3	43°·7	41°·6
December . .	59°·2	35°·6	23°·6	35°·3	33°·3	32°·1
Means . .	103°·4	54°·6	48°·8	67°·1	56°·0	49°·7

The results at Tübingen show that in perfectly fine weather the surface of the soil reached a midday temperature of 120°, or more, from April to September. The highest soil temperature was generally reached in July, the average for that month being 146°·3. Taking the mean for the whole year, the midday temperature at the surface of the soil in fine weather is seen to be 48°·8 above the temperature of the air.

The daily determinations at Geneva, made in all kinds of weather, show that the average midday temperature of the surface soil is about 30° above that of the air in June, July and August, and that at 3 inches below the surface the midday temperature is in the same months 10°–13° above that of the air. For the whole year, the average midday temperature of the surface is 17°·4, and at 3 inches below the surface 6°·3 above that of the air.

The minimum temperatures reached by the surface of a bare, dry soil, freely exposed to the sky, are, on the other hand, considerably below the minimum temperatures of the air. These low temperatures of the soil are the result of the loss of heat by radiation, and occur in the night or early morning when the air is clear, and the sky free from cloud. A thermometer lying on the ground, in an open place, will usually show a lower temperature each 24 hours than a thermometer a few feet above the surface.

When a soil is shaded, or protected by any covering, its range of temperature is much diminished; it receives less heat from the sun during the day, and it loses less by radiation during the night. A mulching of straw or manure will have the greatest influence in this direction. A layer of snow is also very effective in preventing the extreme

cooling of the soil in winter. Boussingault placed a thermometer upon the soil beneath a layer of snow 4 inches thick; another thermometer lay on the top of the snow freely exposed to radiation; a third thermometer was suspended in the air, 39 feet above the ground. The readings of these thermometers during three days of clear weather were as follows. The degrees are centigrade.

Table XXVII

TEMPERATURES BENEATH AND ON THE SURFACE OF SNOW (BOUSSINGAULT)

	In the Air.	Upon the Snow.	Under the Snow.
February 11, 5 p.m. .	+2°.5	−1°.5	0°.0
,, 12, 7 a.m. .	−3°.0	−12°.0	−3°.5
,, ,, 5.30 p.m.	+3°.0	−1°.4	0°.0
,, 13, 7 a.m. .	−3°.8	−8°.2	−2°.0
,, ,, 5.30 p.m.	+4°.5	−1°.0	0°.0

Thus the temperatures of the surface of the ground under the snow were on February 12 and 13, 6°.2–8°.5 C. (11°–15° F.) higher after the night's radiation than those shown by the thermometer freely exposed to the sky.

The shading of a soil by vegetation has a considerable influence in diminishing the extremes of temperature. Crops covering the ground with an abundant foliage will have a distinct effect in this direction.

The soil of a forest, shaded by trees, and further protected by a thick layer of forest litter, affords an extreme example of the exclusion of solar radiation. According to Ebermayer (*Lehre der Waldstreu*, 188), the mean temperature of the soil

of Bavarian forests to a depth of 4 feet is, in June, July, and August, nearly 7° F. less than that of similar soil covered by turf and freely exposed to the sky. In winter, the mean temperature of the two soils was nearly the same. The forest soil was thus on the whole distinctly cooler than the grass land. This coolness of a forest soil doubtless favours that accumulation of humus which is so characteristic of soils of this description. Had the forest soil been compared with arable, instead of with grass land, the differences in the range of temperature observed would have been much more considerable; the turf was, indeed, itself an efficient protection to the underlying soil.

The range of temperature of soil permanently covered with grass is much less than that of soil not so protected; it is, indeed, a common observation, that winter frosts do not penetrate to such a depth under turf as they do in bare soil.

The temperature of the soil may be considerably affected by other circumstances besides the amount of solar radiation. Every circumstance affecting the general temperature of a locality, as altitude, and prevalence of hot or cold winds, will clearly affect the temperature of the soil. Prominent among these circumstances is the neighbourhood of large masses of water. As the temperature of such masses of water is far more constant than the temperature of either the atmosphere or the soil, the neighbourhood of such masses will generally considerably diminish the extremes of heat and cold. The moist and cloudy state of the atmosphere arising from the presence of much water will also act in the same direction. The range of temperature on an island is thus distinctly less than on a continent.

The neighbourhood of large masses of water, by reducing the severity of winter, tends to bring about an early spring. Such situations are thus often extremely favourable for the production of early crops, and are of great value to market gardeners.

Most striking are the differences of temperature determined by the neighbourhood of cold or warm ocean currents. The west coast of Scotland, and the coast of Labrador on the opposite side of the Atlantic Ocean, are in the same latitude, and receive the same solar radiation; but the climate of the first is so warmed by the gulf stream, and the prevalent westerly winds, that fuchsias will live through the winter in the open air; while the temperature of Labrador is so reduced by a cold arctic current that the sea freezes in October, and remains in this condition until April.

Influence of Colour. The amount of heat absorbed by a soil when exposed to the sun's rays depends partly on the colour of the soil. Schübler made the difference of colour as great as possible by lightly sprinkling different portions of the same soil with lamp-black, and with magnesia; the soils thus treated were then exposed to the sun towards the end of August, and the maximum temperature reached one-eighth of an inch below the surface was then observed. The black soils under these circumstances became 13°–15° F. warmer than the white soils. The original character of the soil had little or no influence on the temperature attained in this experiment, provided all the soils were dry; the colour had clearly the preponderating effect.

The excess of temperature shown by a darker soil depends of course on the intensity of the sun's rays. Humboldt, when in the Canary Islands, observed a difference of 25° F.

between the temperature of a black and white sand. Working with natural soils, in a European climate, Schübler, Oemler, and Wollny always obtained the highest temperatures with the darkest soils, humus always heading the list. The extreme differences observed among natural soils did not however exceed 6°–8°. No difference was observed on cloudy days. During the night the dark and light soils cooled to the same point.

The facts just mentioned are easily explained. The white or light coloured soils reflect a portion of the radiation from the sun, while the black soils absorb the whole of it, the total energy of the sun's rays appearing in this case as heat.

It is sometimes erroneously supposed that the darkest soil must cool most, and that the gain of temperature due to a dark colour is followed at night by a loss of temperature due to the same cause. This is not necessarily the case. The absorption in sunlight is influenced by colour, the cooling by radiation at night is not influenced by colour. The absorption in day by black and white surfaces is different, because these surfaces behave differently to rays of high refrangibility; at night both behave alike, because both are then emitting similar rays of very low refrangibility. Melloni found that when lamp-black and white-lead were both exposed to the rays from a lamp flame their relative absorption of heat was 100 : 53; but when the same surfaces were exposed to the radiation from hot water, their capacity for absorbing heat was identical. The emission of heat by lamp-black and white-lead at the temperature of boiling water would necessarily be as equal as their rate of absorption. The extra heat obtained from the sun by a dark soil is thus a substantial gain. Ahr, in his investigation on the radiation

of heat by soil (*Forsch. der Agrikulturphysik*, xvii. 397), found that while different soil constituents radiated heat with different facility, these differences were quite independent of their colour.

The fact that the rays of heat emitted by the warm earth are different in character from the rays emitted by the sun is in several ways very important. The solar rays are but little absorbed by the atmosphere; the radiation from the earth is completely absorbed by moist air. The heat received from the sun is thus retained around the earth when the atmosphere is moist, and night frosts only occur with a clear sky and dry air. The vicinity of water is a great advantage where early crops are to be grown, or where there is a danger of frost in spring or early summer; a small island or peninsula is thus especially well suited for early market gardening. Land irrigated in the spring is also largely free from the effects of frost.

The same facts serve to explain the high temperatures easily obtained in glass-houses exposed to sunshine. The sun's rays pass freely through the glass and are absorbed by the wood, brick, and soil within; these radiate back heat rays of a different kind, which are absorbed by the moist atmosphere in the house, and also by the glass roof. The energy furnished by the sun is thus caught in a trap, it enters the greenhouse easily, and leaves it with difficulty; the temperature within the house thus quickly rises. Frankland (*Pro. Roy. Soc.*, xxii. 319) placed a thermometer in a box lined with black cloth, with a sheet of plate glass as the lid. Exposed to bright sunshine at Davos on December 22, the thermometer rose to 221° F., or 9° above the ordinary temperature of boiling water. Herschel, at the Cape of Good Hope, cooked a beef-steak, and boiled eggs hard, by simple

exposure to the sun in a box covered with a pane of window glass, and placed in another box so covered.

The influence of the colour of the soil on its temperature has been recognized by practical men. In some of the Rhine vineyards it is usual to scatter fragments of black basalt on the surface of the ground, with the object of gaining more heat to ripen the grapes. In parts of Spain, on the other hand, having a much hotter climate, it is only on white soils that certain grapes can be successfully cultivated.

Colour ceases to have a considerable influence on the temperature of the soil when soils are very wet, the extra heat received by dark soils being consumed in the evaporation of water. The power of humus to warm a soil is thus seriously diminished, humus always favouring the retention of water at the surface.

Specific Heat of Soils. Different substances require different quantities of heat to bring them to the same temperature; or, in other words, different substances receiving the same quantity of heat will rise to different temperatures. Thus if a pound of iron and a pound of tin are both placed in boiling water till they have gained that temperature, and are then each of them placed in a similar bulk of cold water, it will be found that the cold water is raised to a higher temperature by the iron than by the tin. By proceeding in this way the relative amounts of heat contained by substances at the same temperature may be measured. As water is of all ordinary substances the one requiring most heat to raise a given weight to a given temperature it is taken as the standard. The numbers representing the specific heat of other substances express the fraction of a unit of heat which is required to raise them to the same temperature that would be reached if

one unit of heat were imparted to an equal weight of water. The calculation may of course be varied so as to show the specific heat of equal volumes. The following determinations of the specific heat of various constituents of soil are quoted from C. Lang.

TABLE XXVIII

SPECIFIC HEAT OF SOIL CONSTITUENTS

	Relative Specific Heat of	
	Equal Weights.	Equal Volumes.
Water	1.000	1.000
Humus (Peat)	0.477	0.587
Magnesium Carbonate	0.260	0.754
Lava and Basalt	0.20 – 0.28	0.54 – 0.84 ?
Clay	0.233	0.568
Calcium Carbonate	0.206	0.561
Quartz, Orthoclase, Granite	0.189	0.499
Ferric Oxide	0.163	0.831

Looking first at the calculations by weight, it appears that the same quantity of heat which would be required to raise 1 lb. of water 1° F., would suffice to raise about 5 lb. of dry chalk or quartz sand, and 2 lb. of peat, to the same temperature. Or, looking only at the solid soil constituents, the same amount of heat from the sun would equally warm about 8 lb. of quartz sand and 3 lb. of perfectly dry peat. It follows, as a matter of course, that when cooling, 3 lb. of peat will evolve as much heat as 8 lb. of quartz sand; and 5 lb. of chalk or quartz as much heat as 1 lb. of water.

The specific heat of a perfectly dry arable soil, reckoned by weight, will generally be ·20– ·23. It follows that 4–5 lb. of dry soil, and 1 lb. of water, will be raised to the same temperature by the same supply of heat.

When we compare the specific heats of equal volumes, we find that water is still far ahead of all the other soil constituents, but the numbers for humus, clay, calcium carbonate, and quartz have become nearly equal. The same quantity of heat would raise to the same temperature 2 cubic feet of quartz, and 1 cubic foot of water. If soils were of the nature of a solid rock, without interstices, and without moisture, they would very uniformly have a specific heat of ·50–·55 when compared with their own volume of water, unless indeed much iron or magnesium were present.

We have already seen that the water-holding power of a soil, viewed in its relation to fertility, is far more accurately stated per unit of volume than per unit of weight (p. 69); the same may be said of the relations of soil to heat. It is the bulk, or depth of the soil that is warmed by the sun, and not the weight, which is important to the plant. To become acquainted with the relations of natural soils to heat on this basis of volume or depth, we must clearly take into account the varying proportions of the bulk which consist of the spaces between the particles; we must also take into account the proportion of water which will be normally present in the soil. The information already given as to the weight of different soils per cubic foot, and as to the proportion of water contained by various soils, both when in an air-dry and in a drained condition, will enable us to calculate the specific heat of soils per unit of volume in various natural conditions.

If, in the first place, we regard soils in the air-dry state, that is containing only hygroscopic water, we find that there is little difference in their specific heat per unit of volume, the coarsest sand, the purest clay, and an air-dry peat, all having specific heats varying from about ·30 to ·42, if the specific

heat of the same volume of water is reckoned as 1·0. This uniformity is largely due to the presence of two factors in varying proportions. The coarse sand contains the smallest proportion of hygroscopic water, but it also possesses the greatest weight per cubic foot. The peat has by much the smallest weight per cubic foot, but it also contains the largest amount of hygroscopic water. In a naturally dry condition a soil will thus have about one-third the specific heat of water; or three cubic feet of soil will be warmed by the sun to the same degree as one cubic foot of water. Of soils in this air-dry condition, peat will have the lowest specific heat, and clay the highest.

The commonest condition, however, in which soils are met with is the condition which is found after rain has ceased, and all excess of water has been removed by prolonged percolation. If we calculate the specific heats of different soils per unit of volume when in this moist, but fully drained condition, we no longer find the uniformity belonging to the air-dry state, the result is now chiefly determined by the amount of water which the soil has retained. A coarse sand, retaining but little water when drained, is now the soil most easily warmed; the fine sands, loams, silts, and clays show a higher specific heat, the figure rising as the proportion of water retained increases. A wet peat is now at the head of the list, and its specific heat differs not greatly from that of its own bulk of water.

Thus, under natural conditions, the driest soil is the one having the lowest specific heat, and therefore (other conditions being equal) the one reaching the highest temperature when exposed to solar radiation. We have already mentioned that it is the soils with coarse particles, retaining little water when

drained, which are always chosen as specially suitable for early garden crops (pp. 20, 57); the reason of this suitability is now apparent—they become warm in spring time earlier than any others.

The influence which oxide of iron has on the specific heat of soils demands further study. The oxide referred to in Table XXVIII was the anhydrous mineral, while the hydrated oxide is the form usually present in soils.

Tillage, by loosening the soil, and thus diminishing the weight in a given volume; and also by diminishing the proportion of water retained at the surface, tends to decrease the specific heat per unit of volume, and so far facilitates the warming of the soil. We shall see however presently that tillage diminishes the power of the soil to conduct heat.

Conductivity of Soil Constituents. The temperature of both the surface soil and subsoil depends in part on the power of conducting heat which the soil possesses. A soil having little power of conducting heat[1] will become very hot on the surface when exposed to the sun during the day, and the surface will become very cold during a clear night when heat is lost by radiation. A soil having a greater power of conducting heat will be warmed to a greater depth by the sun during the day, and the surface will be longer in cooling during the night, as heat will then travel to the surface from the interior. Good conduction thus tends to equalize the temperature of the surface soil, while it occasions a greater range

[1] The 'conduction of heat' is throughout this section used in its popular sense, which would perhaps be more accurately expressed as the 'propagation of temperature.' The quantity of heat transmitted, and its facility of movement, cannot be measured by the rise of a thermometer at a distance from the source of heat. A smaller rise of the distant thermometer may be attended with a greater transmission of heat if the specific heat of the intervening matter is higher than in the comparative instance.

of temperature in the subsoil. Looking at the soil and subsoil together, a greater conduction of heat (other conditions being equal) will be attended with a higher summer temperature, and a lower winter temperature.

E. Pott (*Landw. Versuchs-Stationen*, xx. 288) has compared the power of conducting heat possessed by the principal constituents of soil, and has studied the influence of various conditions on their conductivity. The soil to be studied was placed in a cylindrical vessel, about one foot in length, lying on its side, the bulbs of six thermometers being sunk at equal distances along its axis. The cylinder was surrounded by a non-conducting material. One end of the cylinder consisted of a copper plate; this during the experiment was in contact with the flat surface of a vessel containing hot water. The temperature of the water at starting was in every case 35° C. above that of the soil. The temperature of the water was maintained without alteration during the whole experiment, which lasted in every case twelve hours. The mean rise in temperature of the five thermometers furthest from the source of heat was taken as the figure for comparison. The substances experimented on were quartz powder, and quartz sand of different degrees of fineness; kaolin and potter's clay; levigated chalk (whiting); peat powder. The average results of Pott's experiments are shown in the following statement:—

Relative Conductivity for Heat

1. In air-dry condition

	Lightly shaken together.	*Compressed.*
Quartz Powder	100.0	106.7
Peat „	90.7	98.1
Kaolin „	90.7	96.4
Chalk „	85.2	92.6

Quartz Sand, Fine ...	100.0
" " Medium ...	103.6
" " Coarse ...	105.3

	Dry Quartz Powder = 100.	*Dry Clay* = 100.
Clay Powder	94.1	100.0
" with Limestone Stones ...	112.1	118.8
" " Quartz Stones ...	115.6	122.5

2. In wet condition, not compressed

	Dry Quartz Powder = 100.	*Wet Quartz Powder* = 100.
Quartz Powder	201.7	100.0
Kaolin "	155.6	77.1
Chalk "	153.2	75.9
Peat "	94.3	46.8

Quartz Sand, Dry ...	100
" " Moist ...	174
" " Wet ...	189

Of all the soil constituents experimented with, quartz showed, under every circumstance, the highest power of conducting heat; in this respect indeed it exceeds at least one of the metals, namely bismuth. The conductivity of every substance is greatly lessened when it is in the form of powder; the finer are the particles of the powder the less is the power of conducting heat. The comparative conductivity of different substances cannot therefore be ascertained from experiments on their powders, unless the powders are in every case composed of particles of the same size; the results obtained by Pott are thus only strictly true of the particular powders which he examined. The diminution of conductivity observed in a powder is due to the small extent of contact among the particles; in the case of a dry powder each particle is surrounded by air, in a wet powder each particle is enclosed by water. The far greater conductivity of a solid rock than

of a powder of similar composition is well shown by the experiments made by Forbes and Thomson on the conductivity of the sand of the Experimental Garden at Edinburgh, and of the sandstone of the Craigleith Quarry ; the latter was found to conduct heat about four times better than the former.

Illustrations of what has just been said will be found in the statement of Pott's results already given. It will be seen that the compression of a dry powder increased its power of conducting heat. The coarse sand conducted better than the fine sand. A mixture of equal bulks of stones and clay conducted heat much better than clay alone.

The circumstance having the greatest effect on the conductivity of sand, clay, and chalk was, however, the presence of water. Water is not itself a good conductor of heat; it is indeed in this respect inferior to the solid constituents of soil, but it is a much better conductor of heat than air; the displacement of air by water thus serves greatly to facilitate the transmission of heat. The dry quartz powder had its conductivity doubled when thoroughly wetted. The presence of a little water is sufficient to produce a large effect in this direction. The moist sand contained only 9·9 per cent. of its volume of water; its conductivity was, however, 74 per cent. greater than that of the dry sand. The presence of much water is probably not favourable to the propagation of temperature, owing to the high specific heat which water possesses. It was perhaps for this reason that Pott found that wet peat was apparently a much worse conductor of heat than wet chalk, clay, or sand.

It appears from the facts now mentioned, that a fine, dry, loose soil is the one which conducts heat worst; such a soil will have its surface much heated by the sun's rays, but the heat

will penetrate to a comparatively small depth. On the other hand, a consolidated, stony soil, especially when moist, will prove the best conductor of heat. In such a soil the heat gained from the sun will be most evenly distributed, and will penetrate to the greatest depth. Practical experience has shown that a gravelly soil, having a good aspect, is one especially suited for the production of early garden crops; this is probably due to the rapidity with which such a soil is warmed in spring time. The favourable properties of soils of this character would probably be improved by a top dressing of soot. Such soils provide also some protection from early morning frosts, their good conduction of heat serving then to warm the surface, as during the day it had proved effective in warming the subsoil.

The operations of tillage have a very sensible effect on the propagation of heat through the soil. If the surface soil is brought into a loose pulverulent condition, the passage of heat downwards is retarded. If, on the other hand, the surface is rolled after cultivation, the temperature of the soil beneath the surface is distinctly increased. These results might have been predicted from the facts shown in the experiments described above; they have, however, been confirmed by actual observations in the field made by King in Wisconsin.

In experiments made in six counties, and on soils of various character, he found (*Wisconsin 7th Report*, 120) that the temperature of rolled land at a depth of 1½ inch was 1°–9° F., and at a depth of 3 inches 1°–6° F., higher than that of similar unrolled soil. The average excess of temperature by rolling was 3° F. The temperatures were all taken between 1 and 4 p.m.

We have already seen (p. 113) that keeping a few inches of the surface soil in a loose pulverulent condition by frequent cultivation is an effective method of conserving the moisture of the soil beneath during the heat of summer. One result of this cultivation is to diminish somewhat the temperature of the underlying soil, and this diminution of temperature is in itself favourable to the preservation of water. King (*Wisconsin* 10*th Report*, 190) records observations on the temperature of the soil made in a maize field during the month of July, in ground cultivated 1½ and 3 inches deep. In both the third and fourth foot beneath the surface, the average temperature observed in the day time was 1°·1 F. less where the deepest cultivation was maintained. In later experiments (*Wisconsin* 11*th Report*, 283) he shows that the daily variation of temperature at a depth of 1 ft. was slightly less where the deeper cultivation was adopted.

Radiation of Heat. Several facts relating to the radiation of heat by soil have been already noticed (p. 162), and we have seen that the radiation is independent of the colour of the soil. Ahr (*Forsch. der Agrikulturphysik*, xvii. 397) has investigated the relative radiating power of various soil constituents. The substance was placed in a thin layer, on a cube of warm water, maintained at a constant temperature, and the heat radiated by the substance measured by means of a thermopile and galvanometer. When in a perfectly dry condition, the various mineral constituents of soil proved to be better radiators of heat than the organic constituents. The mineral constituents showed no great difference among themselves; quartz sand was the best radiator.

Water has a greater capacity for radiating heat than any other soil constituent, it even somewhat exceeds soot in this

respect; a moist soil thus radiates heat much better than a dry one. In an air-dry condition, only hygroscopic water being present, the differences between the radiating power of the different solid constituents are only slightly perceptible. In a thoroughly moistened state the distinctions previously observed disappear. All thoroughly moistened soils radiate to nearly the same extent, and the rate of radiation is not increased if the soils are saturated with water. The radiation of heat by a moist soil is nearly equal to that shown by soot.

Ahr points out that the radiating power of a soil by no means determines its rate of cooling, this is largely determined by its specific heat, and its conductivity. A high specific heat will tend to slow cooling. High conductivity will favour a more rapid emission of heat, but a relatively slow cooling of the surface, owing to the passage of heat to the surface from the interior.

Influence of Water on Soil Temperature. We have in the three preceding sections found abundant evidence of the leading part played by water in determining the relations of soil to heat. The action of water in the soil is to diminish its summer temperature. From its very high specific heat, a wet soil shows little rise in temperature when exposed to sunshine. The better conduction of heat in a wet soil (wet peat excepted) tends also to equalize the temperature of the surface and subsoil, and cause it more generally to approach the mean annual temperature. The active radiation of heat from a moist soil leads to loss of heat. The evaporation of water from a wet surface has a still greater effect in cooling the soil, owing to the large amount of heat consumed in converting water into vapour (p. 107). King has calculated that the evaporation of one pound of water

from a cubic foot of wet clay would lower the temperature of the clay 10°·3 F. The loss of heat is nearly the same at whatever temperature the evaporation takes place. The cooling influence of water is so great as to override the influence of other conditions tending to warmth; thus Schübler found that dry soils, coloured white, exposed to the sun, became about 6° warmer than a wet, dark coloured, humus soil, equally exposed to sunshine. The coldness of a soil in summer time is generally in proportion to the amount of water which it permanently retains; it is only during the severer months of winter that a wet soil is superior in temperature to a dry one.

With these facts before us it is easy to understand why a stiff clay or an undrained meadow are said to be cold soils; while a soil of open texture, and well-drained, is said to be warm. Both soils may receive the same heat from the sun; but, in consequence of the properties of water just mentioned, the temperature of the wet soil is always, save in the depth of winter, below that of the dry one. The coldest soil will be one having a permanently saturated subsoil, from which the surface soil is continually replenished with water. The first step towards the amelioration of cold, wet land, will be the removal of the excess of water by draining.

Land in which there is a free percolation of water enjoys generally a special rise in temperature from spring rains. In spring time the rain is frequently warmer than the soil, and if the rain can penetrate the soil it becomes an effective agent for warming it. One pound of rain water at 60° F. would be able, from its high specific heat, to raise the temperature of 10 lb. of dry sand from 45° to 50°.

King's observations in Wisconsin supply some illustrations

of the influence of the water contents of a soil on its temperature. Thus on April 24, between 3.30 and 4 p.m., the temperature of the air being 60°.5 F., the temperature of the surface inch of a wet and dry soil was as follows:—

Well-drained Sandy Loam	...	66°.5
Undrained Black Marsh	...	54°.0

On July 31, the temperature of two soils, each more than half saturated with water, was as follows:—

		First Foot.		*Second Foot.*		*Third Foot.*
Alluvial Sand	...	71°.2	...	70°.1	...	67°.6
Red Clay ...	...	67°.2	...	65°.4	...	63°.6

On August 6, two soils, less than half saturated with water, were found to have the following temperatures:—

		First Foot.		*Second Foot.*		*Third Foot.*
Sandy Loam	...	76°.5	...	74°.7	...	72°.1
Clay Loam	...	69°.5	...	69°.3	...	67°.0

Thus throughout the summer the wetter soil is in every case distinctly the colder.

One of the most instructive illustrations of the influence of water on the temperature of the soil is furnished by the observations made long ago by Parkes on the temperature of a peat bog, known as the Red Moss, in Lancashire (*Jour. Roy. Agri. Soc.* 1845, 140). This bog was 30 ft. in depth, and of the wettest description. Below the depth of 1 ft. the natural bog was found to have a constant temperature of 46° F. during three years of observation. A portion of the bog had been drained by open drains 3 ft. in depth, and the drained portion had been dug to the same depth. Thermometers were sunk to various depths both in the drained and undrained portion. The observations of temperature

given in Table XXIX were made two years after the draining operations just mentioned. The land was without any crop.

TABLE XXIX

TEMPERATURE OF DRAINED AND UNDRAINED BOG (PARKES)

	Depth 7 inches.	Depth 13 inches.	Depth 19 inches.	Depth 25 inches.	Depth 31 inches.
			Drained Bog.		
June 15, 9 a.m. .	57°.6	53°.0	50°.8	48°.6	47°.3
„ 16, 9 a.m. .	60°.0	54°.2	51°.4	49°.0	47°.6
„ „ 3 p.m. .	62°.5	54°.0	51°.8	49°.6	47°.8
„ „ 3.30 p.m.	66°.0	57°.0	52°.0	49°.8	47°.8
„ 17, 9 a.m. .	58°.0	55°.6	52°.8	50°.0	48°.0
			Undrained Bog.		
„ 15–17. . .	47°.0	46°.0	46°.0	46°.0	46°.0

June 15 was a hot cloudless day. June 16 was hot. A heavy thunderstorm took place at 3 p.m.; the temperature of the rain was 78°.

The temperature of the drained bog at 7 inches below the surface is seen to be 10°–19° above that of the undrained bog, and the temperature of the drained portion remains superior even at a depth of 31 inches. The effect of the warm rain on the temperature of the drained soil is very distinct; the temperature at 7 inches beneath the surface rises 3°·5 in half an hour, and the temperature of the subsoil is found next morning to be perceptibly increased. The warm rain has no perceptible effect on the undrained bog.

A saturated peat bog is thus the coldest of all soils in summer time, and the one showing the smallest variation in temperature throughout the year. A dry peat—a heath soil for instance—is, on the other hand, the soil exhibiting the

greatest variation in temperature. According to Mayer, the soils of highest average temperature are those which are dry, dark, and specifically heavy, as those composed of black basalt or dolerite, clay slate, and some sands.

Temperature of Subsoil. The temperature of the subsoil may be affected to a considerable depth by the conditions of temperature prevailing at the surface. At the Observatory at Bombay the soil has an average temperature of about 83° at a distance of 11 ft. beneath the surface. At Jakutsk, in Eastern Siberia, an attempt was made to obtain water by sinking a well, but at a distance of 382 ft. beneath the surface the soil was still frozen. The mean temperature of the air in this locality was about 15° F. In many parts of North America and Siberia crops are annually raised in summer time upon the thawed surface soil, the subsoil remaining permanently frozen.

In the tropics, where day and night are of nearly equal length throughout the year, and summer and winter are unknown, the variations in the temperature of the subsoil are but small; but in higher latitudes, where the seasons are very different in character, the range of temperature in the subsoil becomes very considerable. The range of variation is in all cases greatest near the surface, and becomes smaller and smaller at increasing depths.

At a certain depth in every soil a point is reached at which the variations of the temperature at the surface cease to be felt. The daily variations of temperature caused by the alternations of day and night are seldom perceived below 3 ft. from the surface. The effects of summer and winter may be felt at a much greater depth, but a point is at last reached at which the thermometer remains unchanged throughout the

year. The position and temperature of this point vary much in different climates, and in different soils. It is to be regarded simply as a point of equilibrium. In hot climates there is a warmer soil above this point, and a cooler soil below it. In cold climates the soil is cooler above and warmer below.

The depth at which a constant temperature is reached is greater the greater are the variations in annual temperature at the surface. In the tropics a constant temperature is usually found a few feet beneath the surface; in higher latitudes the depth is generally very considerable. The distance from the surface at which variations of temperature can be felt is however considerably affected by the conductivity and specific heat of the soil or rock of the locality; observations at different places thus frequently differ even when these places are in nearly the same latitude. We have already seen that in the case of an undrained Lancashire bog, the temperature remains practically constant throughout the year at a depth little exceeding one foot.

The average annual range of temperature observed at various depths of soil at the Observatories of Greenwich, Brussels, and Edinburgh is shown below; the degrees are Fahrenheit. The soil at Greenwich is gravel. At Edinburgh the temperatures are taken in a drill-hole bored into a porphyry trap-tuff rock.

Average annual Range of Temperature at various depths

	Greenwich.	*Brussels.*	*Edinburgh.*
1 inch	25°.4		
7½ inches ...	...	... 23°.9	
1.5 feet	...	... 22°.3	
2.5 „	...	... 20°.5	

	Greenwich.	Brussels.	Edinburgh.
3.2 feet	21°.4	19°.3	16°.8
6.4 ,,	15°.1	...	10°.2
12.8 ,,	9°.3	8°.1	5°.0
25.6 ,,	3°.4	2°.0	1°.3

In none of these instances is the point reached at which no variation of temperature is observed. H. Fritsche (*Repertorium für Meteorologie*, 1872) has calculated from the observations made at Upsala, Edinburgh, Paris, Strassburg, and Zürich, the average depths at which the annual variation will amount to 1°.0, 0°.1, and 0°.01 C.; his results are as follows:—

Annual Temperature Variation.		*Average Depth of Soil.*	
Centigrade.	Fahrenheit.	Metres.	Feet.
1°.00	1°.80	8.55	28.04
0°.10	0°.18	15.35	50.34
0°.01	0°.02	22.37	73.36

The variations of temperature immediately below the surface depend very much on the exposure at the surface. At observatories a hut is usually placed over the soil thermometers for the protection of the stems which rise above the surface. The soil in which the shallow thermometers are placed is thus neither heated by direct sunshine, nor exposed to night radiation. The extent of variation at a short distance below the surface is thus much smaller than would occur in an open field. Schübler's determinations of midday temperatures at Geneva (Table XXVI) show a variation between the monthly means of 43°.6 at 3 inches, and 30°.5 at 4 feet. The mean monthly temperatures in Pennsylvania (Table XXX) also show a variation of 40°.8 at a depth of 6 inches.

Soil being a bad conductor of heat the alterations of temperature at the surface pass but slowly downwards, and affect the temperature of the subsoil long after the effect on the

surface has ceased. Thus the date of maximum temperature in the subsoil occurs later and later in the year with increasing depths, till at a certain point the maximum temperature in the subsoil takes place at the same time as the minimum temperature at the surface, and the seasons are reversed. At still greater depths the maximum may occur yet later, till its influence disappears altogether. The average dates of maximum and minimum temperature at various depths of subsoil at Greenwich and Edinburgh are as follows:—

	Greenwich.		*Edinburgh.*	
Depth.	Maximum.	Minimum.	Maximum.	Minimum.
3.2 feet	Aug. 9	Feb. 8	Aug. 16	Feb. 21
6.4 "	" 25	" 24	Sept. 2	March 19
12.8 "	Sept. 25	March 27	Oct. 15	April 22
25.6 "	Nov. 30	June 1	Jan. 6	July 8

The passage of heat through the Edinburgh soil is evidently slower than through that at Greenwich.

In temperate climates, in the northern hemisphere, the subsoil at moderate depths will be cooler than the surface soil from April to August, and warmer than the surface from September to February or March. The precise date at which the relation changes depends on the depth in question, and on other local conditions. Towards the end of September, and in March, a fairly uniform temperature will be found to a considerable depth in the subsoil. The general relations of the temperature of the subsoil at moderate depths to those observed at the surface, and in the air, will be gathered from the following table containing the observations made at the Pennsylvania State College in 1893. The soil is described as a compact loam for the first seven inches, the subsoil being a stiff clay. The neighbouring soil is covered with turf, but

the soil immediately over the thermometers is kept free from vegetation.

TABLE XXX

MEAN MONTHLY TEMPERATURES OF AIR AND SOIL, PENNSYLVANIA, 1893

	Air.	Soil.			
		1 inch.	6 inches.	12 inches.	24 inches.
January . . .	18°.0	26°.3	29°.0	31°.4	33°.8
February . .	26°.0	28°.3	29°.5	31°.2	32°.6
March . . .	33°.5	31°.5	31°.3	31°.9	32°.8
April . . .	46°.3	42°.9	40°.9	40°.8	39°.7
May	57°.1	54°.5	53°.7	52°.9	50°.6
June	68°.7	66°.3	65°.6	64°.7	61°.8
July	70°.7	69°.8	69°.8	69°.0	66°.6
August . . .	68°.8	68°.8	68°.4	69°.4	68°.1
September . .	60°.5	60°.3	62°.4	63°.4	63°.9
October . . .	52°.2	51°.4	53°.5	54°.9	56°.2
November . .	37°.9	38°.4	40°.9	43°.1	45°.9
December . .	31°.9	32°.1	34°.0	36°.0	38°.0
Mean . .	47°.6	47°.6	48°.3	49°.1	49°.2

The temperature of the subsoil is affected not only by the varying temperature of the soil above it, it is affected equally by the less varying temperature of the soil beneath it; the temperature of every particle of soil is in fact the mean of the temperatures of the particles surrounding it. Towards the end of winter, the heating of the subsoil from below is often very apparent. To perceive this we must study the temperature of a layer of subsoil equidistant from layers above and below it, the temperatures of which are also determined. An excellent opportunity of doing this is afforded by the observations made at Pekin by H. Fritsche (*Repertorium für Meteorologie*, ii).

Mean weekly Temperatures of Soil, Pekin, 1870

	Depth 0.549 m.	Depth 1.090 m.	Depth 1.646 m.
February 22 ...	0°.21 C. ...	3°.14 C. ...	5°.84 C.
March 1	1°.43 ...	3°.34 ...	5°.54
„ 8	3°.24 ...	4°.17 ...	5°.86
„ 15	4°.23 ...	4°.93 ...	6°.30

It is evident at a glance that the temperature of the intermediate layer of soil is rising during the period under observation; it is equally evident that the rise is not due to the heat from above, as the soil above is cooler than the intermediate layer during the whole of the period. The rise is clearly due to an accession of heat from below. The difference of temperature is in fact greater between the intermediate layer and the warmer soil below, than between it and the cooler soil above, and the movement of the temperature in the intermediate layer is determined by the greater of these two forces. The popular idea that a frozen soil often thaws from beneath as spring approaches is thus perfectly correct.

The mean temperature of a soil is not far from that of the air above it. The greatest disturbance to this general rule is occasioned by snow. A covering of snow in winter time greatly diminishes the cooling of the soil in severe climates. In parts of Russia the soil has a mean annual temperature 9° F. in excess of the air as a consequence of this protection during winter.

In temperate climates the mean temperature of the subsoil increases slowly with increasing depth. At Edinburgh, as a mean of 40 years' observation, the mean annual temperatures at various depths have been as follows:—

Depth 3.2 feet ...	46°.34 F.
„ 6.4 „ ...	46°.60
„ 12.8 „ ...	46°.99
„ 25.6 „ ...	47°.25

Many irregularities must be expected in observations on subsoil temperature. The melting of snow in spring may at once determine an abnormal cooling of the subsoil, while heavy rain in early summer will at once convey the heat of the surface soil to the lower layers. If any part of the subsoil holds more water than the soil above and below it, this portion of the subsoil will display an irregular temperature[1].

Prevention of Summer Frost. Immense damage is occasionally done to growing crops in certain districts by early morning frosts. These injurious frosts are most common in the spring or early summer, or again in the early autumn before harvest. In the spring they are dreaded by the fruit grower, even in climates as mild as those of Italy or Florida. In late summer they are disastrous to the yet unripened cereal grain, maize or wheat, in Canada, and in the more northern of the United States. In countries such as Finland, which lie near the extreme limit of possible cultivation, summer frosts will not unfrequently destroy all the crops and produce a famine.

The conditions which produce these unseasonable frosts are well understood. The frost arises from the unchecked radiation of heat from the surface of the earth, or more particularly from the surface of the growing plant. The rapid loss of heat during the hours succeeding sunset culminates shortly before sunrise, and the surface temperature of all bodies exposed to the sky is then found to have sunk below the freezing point. For this rapid radiation of heat to occur it is necessary that the sky should be free from cloud, the air very dry, and perfectly still and calm. The clearness of the sky, and dryness of the air, prevent the retention of radiant heat by the

[1] The Report by H. Mellish on the subsoil temperatures at stations of the Roy. Meteor. Society was issued after the above section was in type.

atmosphere (see p. 151), while the absence of wind prevents the warmer air of greater altitudes or of surrounding districts from counteracting the rapid cooling which is in progress.

The conditions necessary for the production of frost being so few and simple, a careful observer should have no difficulty in predicting its occurrence, especially if he is able to ascertain the state of dryness of the atmosphere by means of a hygrometer. In the United States the prediction of frost over wide areas is one of the functions performed by the Weather Bureau. Slight frosts are, however, often confined to well-marked localities; low-lying land is especially likely to suffer, the fall in temperature being assisted in this case by the descent of cold air from the higher regions around.

It has been known from ancient times that the production of smoke when frost is apprehended will often be the means of saving a crop from injury. Pliny apparently refers to this practice (Book xviii, chap. 69, 70); he says:—

'The moon, however, is productive of no noxious effects at either of these periods, except when the nights are clear, and every movement of the air is lulled; for so long as clouds prevail, or the wind is blowing, the night dews never fall. And then, besides, there are certain remedies to counteract these noxious influences. When you have reason to fear these influences, make bonfires in the fields and vineyards of cuttings or heaps of chaff, or else of the weeds that have been rooted up; the smoke will act as a good preservative.'

Boussingault in treating of this subject (*Chimie agricole*, ii. 378) quotes also from the *Commentarios reales* of the Inca, Garcilaso de la Vega, showing that before the conquest of Peru, the Indians at Cuzco on the flanks of the Andes,

11,000 ft. above the sea, were in the habit of burning heaps of manure as a sacrifice to the sun on clear nights, in order to secure the protection of the maize from frost. Boussingault mentions that the same practice of producing smoke as a protection against frost is employed in some of the vineyards and olive gardens in France; the smoke is needed only in the early morning from 3 a.m. to sunrise.

Lemström in Finland has recently developed this plan of protection, with the view of diminishing the serious losses from which his countrymen suffer (*Exp. Stat. Record*, v. 660). Later information as to the method is given by King (*Wisconsin 12th Report*, 253). Hollow cylinders of peat mud are moulded by machinery; their length is 10 inches, their external diameter 7 inches, their internal diameter about 1¾ inch. Each cylinder, or torch, is provided with a smaller lighting cylinder, about 2 inches long. When the torch is to be kindled, the smaller cylinder is wetted with petroleum, and inserted a little more than its own length into the larger cylinder, which is placed in a sloping position; a light is then applied. The larger cylinders are kept in their places in the field ready for action. If the field is in the midst of level ground, it is surrounded by torches, one being placed at every five steps; torches are also placed across the field at every twenty-five steps. If the field is exposed in any direction to currents of cold air, these must be cut off by placing torches at every three steps. If, on the other hand, it is protected by a wood, or is intersected by ditches which do not enter it from a higher level, then the number of torches may be diminished. The number of torches required for one acre is reckoned as 90–130; for five acres, 270–320; for ten acres, 500–550; for twenty-five acres, 1,100.

The protection is believed to arise in several ways: firstly, by the check to radiation produced by covering the field with smoke; secondly, by the upward movement of air established round the field; thirdly, by the actual heat produced.

Lemström claims that the above plan has met with considerable success in Finland. King has made some trials of it in Wisconsin with no great result; he points out, however, that success will be greatest when the frost is most unseasonable, when, in fact, the general body of the air is quite above the freezing point. Possibly, too little attention has been given to the kind of smoke produced; the smoke furnished by damp materials should be the most effective in preventing loss of heat by radiation.

In the United States Agricultural Year Book for 1895, p. 143, an account is given by B. T. Galloway of various methods for preventing injury from frost employed in California, and other parts of the States. Valuable fruit and garden crops are protected by light wooden frames, 6 × 3 ft., on which oiled muslin is stretched; the protection is said to be nearly equal to glass. Movable screens, made of laths fastened together with wire, are also employed, both for protection against frost, and for shading from the sun; when not in use they can be rolled up. Some orchards are provided with kettles of coal tar, placed at suitable intervals, these are lighted with petroleum, and produce an abundant flame and smoke. In other places cheap petroleum is carried by a main through the orchard; when frost is feared the petroleum is allowed to discharge into kettles, and is set on fire.

The most effective and elegant method for the prevention

of frost described by Galloway is the production of a fine spray of water above the summits of the trees. The orchard is provided with standard pipes, 40 ft. in height, connected with an underground main; ten of these standards are required for an acre. Each standard terminates above in a cross pipe 4 ft. in length, the two ends of the cross pipe being furnished with fine cyclone nozzles turned upwards. The supply of water to the main is made in the watchman's house. As soon as the temperature falls to freezing, an electric alarum rings in the watchman's house, he then turns on the water, and the orchard is presently covered with a fine fog-like mist about 45 ft. above the ground.

We have already (pp. 160, 163) called attention to the great influence which the neighbourhood of large masses of water, or the employment of water for irrigation, has in securing immunity from frost.

CHAPTER V

MOVEMENTS OF SALTS IN THE SOIL

Salts in the Soil—Diffusion of Salts—Influence of Movements of Water—Phenomena of Drainage Waters—Alkali Lands—Treatment of Alkali Lands.

Salts in the Soil. The water present in a fertile soil always contains salts in solution; the quantity of salts dissolved in the water is usually very small, but their importance for plant nutrition is very great. A part of these salts is annually taken up as plant food by the roots of the crops growing on the land; a part is also annually removed by percolating water, and is discharged by springs into rivers, and finally carried to the sea. The loss of salts which thus takes place is met by annual supplies. The rain brings small quantities of certain salts to the land. The decay of vegetable and animal matter returns soluble salts to the soil which had previously existed in their tissues. The gradual solution of some of the soil constituents may also considerably increase the quantity of salts present.

The salts most generally produced in the soil by this process of solution are calcium carbonate, resulting from the solvent action of water containing carbonic acid on the calcareous constituents of the soil, and calcium nitrate, produced during the process of nitrification. The solution of

calcium carbonate may occur throughout a considerable depth of soil, though most vigorously in its upper layer. The production of nitrate is practically confined to the surface soil.

Besides the calcium and magnesium salts derived from the calcareous matter in the soil, soluble salts of potassium and sodium may also arise if the soil contains imperfectly weathered silicates.

Considerable quantities of salts are sometimes applied to the surface of the soil in the form of manure. Nitrate of sodium, sulphate of ammonium, potassium salts, chloride of sodium, soluble phosphates, and sulphate of calcium are applied in this way. Some of the substances thus applied are chemically retained by the soil, and need not therefore be considered when we speak of the movements of salts within the soil. This retention by the soil depends however upon the quantity of the material applied, and if this quantity exceeds the retentive power of the surface soil the movement of even these salts becomes quite possible. We need not at this point discuss the relative retentive power of soils for the various bases and acids; we need only note that soil has apparently no retentive power for the acid radical of nitrates, chlorides and carbonates, and very little for the acid radical of sulphates; and that when these acid radicals occur in soil solutions they are usually combined with calcium or sodium. On the other hand, phosphoric acid, potassium, and ammonium are only rarely present to any considerable extent in soil solutions, these substances being generally precipitated on the surface of the soil particles, and retained there in a difficultly soluble condition.

In a wet soil the solution of salts moistening the solid particles is usually very weak. As a soil dries the solution

becomes much more concentrated; and when this concentration reaches a point exceeding the solvent power of water, the salts previously held in solution will be deposited in a solid form. As the evaporation of water takes place from the surface of the soil, it is on the surface that deposits of salts from solution chiefly occur. If the soil water is brought to the surface by capillary action, an accumulation of salt may form on the surface in dry weather, and be visible to the eye as a delicate white crust or efflorescence. In the case of fertile soils, these white films will be of rare occurrence, unless superphosphate, or other manure supplying sulphate of calcium (a salt of little solubility), has been applied to the land. In the alkali lands of India and California, however, the accumulation of salts at the surface reaches serious dimensions, and may suffice to destroy all plant life. The salts present in alkali lands are principally the sulphate, chloride and carbonate of sodium.

It is evident from what has been already stated that the soluble salts in a soil are subject to a variety of vicissitudes. They may be concentrated in a solid form, or as a strong solution, at the surface; this being especially the case after active nitrification, after drought, or especially, and to the greatest extent after the application of a dressing of saline manure. Opposed to this tendency to accumulation at the surface we have the action of rain, which washing the surface soil with nearly pure water tends to carry all soluble salts into the subsoil. Equally opposed to accumulation is the action of diffusion, which, in a moist soil, tends to equalize the proportion of salt throughout the whole mass.

The movements of salts in the soil are thus determined by two agencies—partly by the diffusibility of the salt in

water, and partly by the actual movements of water within the soil. The greatest movements of salts are occasioned by the latter cause, but the influence of the former is by no means insignificant.

Diffusion of Salts. If a solution of any salt is placed in contact with pure water the salt at once commences to distribute itself throughout the water, and, if sufficient time is allowed, the whole mass of water becomes at last a solution of uniform composition. This movement of the molecules of salt in water is akin to the self-distribution of the molecules of a gas in air; it will occur in the absence of all movement in the water, and is indeed best studied by experimenting with masses of solid jelly, in which the diffusion of salts is quite as active as in fluid water.

The rapidity of diffusion depends on the difference in the concentration of the salt in adjacent parts of the mass of water; the greater the difference the more rapid is the diffusion. Thus salt will diffuse more rapidly into water from a strong solution than from a weak; and more rapidly into pure water than into a weaker solution of the same salt. If we suppose a saturated solution of a salt placed at the bottom of a vessel of pure water, we have at starting a maximum rate of diffusion. Presently, however, the strong solution at the bottom is diffusing into a weaker solution of salt lying above it, and the pure water in the upper part of the vessel is in contact, not with a strong, but with an extremely weak solution of salt lying under it. The speed with which the salt spreads through the water will thus rapidly diminish, and in the final stages of the diffusion process becomes extremely slow.

For cases in which the concentration of the diffusing salt

solution is maintained unaltered at one end of a cylinder of water, the total quantity of salt which diffuses, and the distance travelled by the salt, are both proportional to the square root of the time of diffusion, so long as any pure water remains in the cylinder. Thus the amount of salt diffusing in twenty-five hours would be only five times the amount diffusing in the first hour. The case here assumed would practically occur when any top dressing of a soluble salt is applied to a wet soil, and would continue so long as a saturated solution of that salt remained at the surface. As soon however as the concentration of the diffusing salt solution is diminished the rate of diffusion will considerably decrease.

Within certain limits, the rate of diffusion is proportional to the strength of the salt solution, a solution of twice the strength diffusing twice as much in the same time.

Though a salt diffuses into a weak solution of the same salt much more slowly than into pure water, it will diffuse into a solution of another salt with nearly the same speed as into pure water. This fact is of great importance, and much increases the practical effects arising from diffusion. If in any part of a moist soil a salt is removed from solution by the action of roots, or by the chemical absorption of the soil, a flow of that salt will take place at once towards the spot, irrespective of the quantity of other salts which may be present.

Diffusion is considerably influenced by temperature, and becomes more rapid as the temperature rises. Thus Graham found that when the temperature of the solution was 67° F. chloride of sodium diffused rather more than one-third more rapidly than when its temperature was 39°·6.

Different substances have very different rates of diffusion.

For our present purpose we need only notice those substances which may occur in solution in the soil [1]. Colloid substances have the lowest diffusibility. The diffusibility of a salt is determined partly by its acid, and partly by its basic constituent.

The most diffusible salt of any metal is the chloride; the nitrate is but little less diffusible; the sulphate is considerably less diffusible than either chloride or nitrate; the carbonate is rather less diffusible than the sulphate. The diffusibility of phosphates does not seem to have been determined; the subject is however of little agricultural importance, as phosphoric acid occurs only in very minute quantity in soil solutions, and when applied in a soluble form as manure it is quickly precipitated upon the surface of the soil particles.

Of the ordinary bases, the most diffusible is potassium; then follow, in a decreasing order, ammonium, sodium, calcium, and magnesium. As potassium and ammonium are somewhat readily removed from solution by a fertile soil, their distribution by diffusion cannot generally be long continued.

Some idea of the comparative diffusibility of the acids and bases just named will be gathered from the results of some of Marignac's experiments (*Ann. Chim. Phys.* [5], 2, 579), given in Table XXXI. In each of these experiments equal weights of two salts were dissolved together in water—in the cases selected 2·5 grams of each salt in 100 of water—and the solution placed in an open, wide-mouthed bottle, which it nearly filled, pure water being added till the upper edge was reached. The bottle containing the mixed salt solution stood in the middle of a much larger vessel, which was subsequently carefully filled with water. At the end of

[1] A good general account of the phenomena of diffusion will be found in Mr. Pattison Muir's translation of W. Ostwald's *Solutions*.

some days the bottle was removed, and the quantity of each salt which had diffused out of the bottle was ascertained. The comparative diffusibility of the two salts, under perfectly equal conditions, was thus ascertained. By taking the diffusibility of one salt as a standard throughout each series of trials in which a variety of salts was employed, the comparative diffusibility of these salts was ascertained. The 'diffusion coefficient' for each salt was calculated by a formula given in Marignac's paper. The numbers given in Table XXXI are comparative only, the standard salt in each series being taken as unity. The comparison holds good only between the numbers contained in the same column.

TABLE XXXI

RELATIVE DIFFUSION COEFFICIENTS OF SALTS (MARIGNAC)

Relative Diffusibility of Acids.		Relative Diffusibility of Bases.			
Potassium Salts.		Chlorides.		Sulphates.	Nitrates.
Chloride . .	1.14	Potassium . .	1.56	1.46	1.55
Nitrate . . .	1.00	Ammonium .	1.25	...	...
Sulphate . .	0.60	Sodium . . .	1.00	1.00	1.00
Carbonate . .	0.50	Calcium . .	0.65	...	0.66
		Magnesium .	0.55	0.51	0.64

Although the plan of diffusing two salts together, when it is desired to ascertain their relative diffusibility, has many advantages, the results obtained are not quite those which would be found if the salts were diffused separately. In an experiment with a mixture, the rate of diffusion of the more diffusible salt is generally very nearly what it would be if diffused alone, while the rate of diffusion of the less diffusible

salt is distinctly diminished. The relative diffusibility of the two salts is also sometimes affected by the strength of the solution employed. In some cases—as in mixtures of potassium nitrate with potassium chloride, or of sodium nitrate with sodium chloride—the more dilute is the solution, the more nearly do the rates of diffusion of the two salts approach each other. In other cases—as in mixtures of potassium nitrate and carbonate, or of the chlorides of sodium and magnesium—the amount of dilution does not affect the relative diffusibility of the salts. The subject is thus one of some complexity.

Some of the facts just mentioned are of considerable agricultural importance. The salts having the greatest value as plant food—the nitrates, and the salts of potassium and ammonium—are also those which will diffuse most rapidly in the soil. In selecting manures it is well to remember that the chlorides of potassium, sodium, and ammonium will distribute themselves much faster when applied to a moist soil than the corresponding sulphates. The differences in the diffusibility of the bases are also of practical importance. Nitrate of sodium will clearly diffuse in the soil much more rapidly than nitrate of calcium. This fact indicates an additional difference between the behaviour of nitrate of sodium and ammonium salts when applied as manure to a soil, the nitrification of the latter in the soil resulting, as is well known, in the production of nitrate of calcium.

The different diffusibility of different salts will of course occasion their separation in the soil, the most diffusible salt always travelling fastest. Graham diffused a mixture containing equal weights of chloride and sulphate of sodium; in the most distant part of the solution the proportions found

were chloride 90·6, sulphate 9·4. Kainite when applied to a moist soil must be quickly separated into its constituent salts, the potassium, sodium, and magnesium compounds having each very different rates of diffusion. A similar separation of the constituents will occur when any saline mixture is applied to the soil.

Urea, according to Graham, is a substance of very considerable diffusive power, nearly equal in this respect to sodium chloride. As urea is also not retained by soil, it is clear that the application of fresh urine to soil will result in a distribution of nitrogenous matter within it, similar for a time—till the conversion of urea into ammonium carbonate has taken place—to that occurring after an application of sodium nitrate.

Illustrations of the results produced by the diffusion of salts in the soil will be found further on.

Influence of Movements of Water. It will be readily understood that any movement of the water in a soil, whether of the nature of a downward percolation, or of a rise brought about by capillary action, must carry with it the salts which the water holds in solution. The effects which will follow the descent of pure rain water upon the surface of a soil are not so obvious. In considering this, the most common action of water on soil, we must distinguish between two cases, namely whether the soil is dry or wet when the rainfall takes place.

If a steady and continued rainfall takes place on the surface of a homogeneous soil, free from fissures, and in a dry condition, the water descends through the soil as a liquid column; the lower surface of this column continually dissolves the salts it meets with, while the column is pushed further and further into the soil by the continual additions of rain

water at the surface. After a short time the upper layer of the soil, through which the column of water has passed, will be found entirely free from soluble salts (saving of course those contained in the rain, or those formed by a new chemical action on the soil), while at the lower surface of the descending column there will be found a narrow layer of concentrated salt solution, containing all the salts which have been removed from the surface soil. If this narrow layer or band of salt solution during its passage downwards reaches an outfall, as for example a bed of gravel, the salts carried down by the rain are permanently removed from the upper soil.

For the action just described to take place in its most striking manner, it is necessary that the rainfall should be considerable and continuous; for diffusion is always at work, tending to re-establish the equal distribution of salts in the wet soil. With a heavy rainfall, occurring in a short time, the layer of salt solution carried downwards will be very narrow and highly concentrated. If, on the other hand, the rainfall is light and long continued, the layer of salt solution will be wider and the solution weaker. In any case, as soon as percolation ceases, the salts carried down will begin to distribute themselves again in all directions through the wet soil, unless in their downward course they have reached an area of discharge, and have thus been removed from the scene of action.

If, however, the soil is moist when rain commences, although we have, as before, the same descending column of rain water, we have no longer a layer of highly concentrated salt solution pushed before it; the rain water now simply displaces the solution already existing in the soil, and pushes this before it in a practically undiluted condition.

Should the soil in question be rich in porous particles, in humus for instance, the action of the descending water column will be less perfect than we have supposed, the salt solution in some of the pores remaining undisturbed for a sufficient time to affect the result. The first discharge from the soil under these circumstances will consist, as before, of the unaltered soil solution; but the whole of the soil solution will not be discharged unaltered, the latter portion appearing in a diluted form.

Schloesing (*Chimie agricole*, 127) has made considerable use of the method of displacement in order to procure for examination samples of the solutions naturally present in the soil. Working with non-porous sand, he was able to obtain 85 per cent. of the solution which it contained in an unaltered form by displacement with water. With a soil of very varied physical constituents, only about 20 per cent. of the original solution was collected unaltered, the remainder coming through more or less diluted. In Schloesing's experiments the water was sprinkled on the surface of the soil, and percolation took place by gravitation only.

More striking results are obtained when a uniform powdered soil is employed, and the water is made to descend more rapidly by means of an air pump. The following experiments were made by myself in the Rothamsted Laboratory (*J. Roy. Agri. Soc.* 1881, 329). The percolator used consisted of a half-gallon bottle from which the bottom had been removed; this was fixed mouth downwards, thus forming a large cylindrical funnel. In this funnel was placed a disk of fine wire-gauze, covered by a rather larger disk of filter paper, and on this 7 lb. of finely powdered, air-dried loam; the soil was well shaken in, so as to lie as compactly as possible. The column

of soil thus prepared was about eight inches in height, and 4½ inches in diameter. The neck of the funnel was connected by a cork and tube with a flask placed beneath. The flask was then connected with a filter-pump, so that a diminished pressure was produced in the flask and in the mass of soil above it. Distilled water was next gently poured on the surface of the soil, the supply of water being steadily maintained so that the surface was always supersaturated. One great advantage of the connexion with the pump was that the air in the soil was removed as the water descended through it; when no pump is used, the air is apt to escape upwards through the wet soil, the mass consequently becomes broken, and the displacing action of the water is disturbed.

In 2¼ hours the whole column of soil had become saturated, and dropping into the flask commenced. The drainage water was collected in several portions, and the quantity of chlorine and nitric acid in each portion was ascertained. The results are shown in Table XXXII.

TABLE XXXII

COMPOSITION OF DRAINAGE WATER OBTAINED BY PERCOLATION THROUGH A PREVIOUSLY DRY SOIL

Water put on.	Drainage Water obtained.	Composition of Drainage Water.			
		Chlorine.		Nitrogen as Nitric Acid.	
Grams.	Grams.	Per Million.	Grams.	Per Million.	Grams.
900	50	1068.5	0.05343	188.3	0.00942
50	50	266.0	0.01330	82.7	0.00414
50	50	21.3	0.00106	8.0	0.00040
100	100	none	none	1.7	0.00017
1100	250		0.06779		0.01413

It appears from these figures, that the soil, weighing about 3,175 grams, and containing probably about 5 per cent. of moisture, was saturated by the addition of 850 grams of water. The first 50 grams of water which passed through after saturation contained rather more than three-fourths of the chlorides and nitrates originally present in the soil, and practically the whole of the soluble salts was removed in the first 150 grams of drainage water[1]. The process of soil extraction was completed in less than four hours.

The illustration just given shows in a forcible manner how salts are carried through the soil when a heavy rain falls on previously dry earth, and the process of percolation is speedily accomplished, so that diffusion is reduced to a minimum. In the next experiment to be mentioned, the soil was saturated with water before the experiment commenced, and percolation took place very slowly; opportunity was thus given for the action of diffusion to be manifested.

The object of the next experiment was to study the passage through the soil, and the discharge into the drainage water, of a dressing of saline manure applied at the surface. A column of soil, quite similar to that used in the previous experiment, had all its soluble salts removed by extraction with water aided by the air-pump in the manner before described. The mass of saturated soil was then disconnected with the pump, and 0·3843 gram of chloride of sodium, dissolved in a little water, was distributed over the surface. The chloride of sodium contained 0·23313 gram of chlorine; it was equivalent to a dressing of 3 cwts. of common salt per acre.

[1] This mode of extracting the soluble salts present in a soil is so simple and effective that it has been largely adopted when determinations of the nitrates or chlorides present in a soil are desired. *Trans. Chem. Soc.* 1882, 351.

After standing undisturbed for a week, 120 grams of water were placed on the surface of the soil, and the same application of water was continued daily till the end of the experiment. Each day about 120 grams of drainage water were collected, and examined for chlorides. No pump being used, nearly twenty-four hours were required for the percolation of 120 grams of water. The results of the analysis of the successive drainage waters are shown in Table XXXIII.

TABLE XXXIII

COMPOSITION OF DRAINAGE WATER AFTER CHLORIDE OF SODIUM HAD BEEN APPLIED TO THE SOIL

Water put on.	Drainage obtained.	Chlorine in Drainage Water.	
Grams.	Grams.	Per Million.	Grams.
120	117.1	none	none
120	119.4	none	none
120	115.1	none	none
120	120.2	43.8	0.00527
120	115.3	202.0	0.02329
120	118.9	476.0	0.05659
120	114.0	621.0	0.07079
120	123.4	425.0	0.05245
120	118.9	158.0	0.01879
120	120.0	39.8	0.00478
120	119.4	7.6	0.00091
1320	1301.7		0.23287

It appears from the facts mentioned in the table that the chloride of sodium commenced to appear in the drainage water after 480 grams of water had been applied to the soil. It is evident at once that the chloride of sodium must have

diffused downwards to a considerable extent during the ten days that had elapsed since its application; for had the chloride remained entirely at the surface it would have required 850 grams of water to carry it through the soil, this being the quantity of water required in the previous experiment to saturate this mass of soil, and consequently the amount necessary to displace the water contained in the soil when already saturated.

Fresh proof of the activity of diffusion is furnished by the composition of the successive discharges of drainage water. The drainage is not at its maximum strength at first, as in the previous experiment. The chlorides when they first appear are small in quantity, and the strength of the discharge rises rapidly during four days, and then diminishes in an equally gradual manner. A glance at the proportion of chlorine per million of water shows that a band of salt solution was passing downwards through the soil during the experiment, and that the salt was during the whole time actively diffusing from the upper and lower surfaces of this band into the soil saturated with water through which it was moving.

The slower is the passage of water through the soil, the larger is the quantity of water required to remove the soluble salts. In the first experiment, all the chlorides were removed from the soil in four hours, by the use of 1,000 grams of water. In the second experiment, lasting eighteen days, 1,320 grams of water were required to accomplish the same work. The effects produced by diffusion become very considerable whenever time is allowed for their manifestation, and these effects are in the main conservative, and tend to counteract the removal of salts from the soil by rain water. Very heavy or continuous rains are very injurious to fertility, the surface

soil being thus deprived of soluble plant food; intermittent showers are far more beneficial. The injury due to heavy rain will be felt to the greatest extent by shallow-rooted plants. Deep soils are those most favourably circumstanced for the conservation of soluble salts, the matters carried down by rain from the surface having here the greatest opportunity of rising again by diffusion when rain has ceased.

Phenomena of Drainage Waters. In field soils the action of rain in washing out the soluble salts near the surface is by no means so extreme as we might suppose from laboratory experiments made with powdered soils, yielding a uniform solid mass when wet. A natural soil always contains numerous channels and fissures; the former produced by roots which have afterwards decayed, or by the passage of worms; the latter by contraction during drought. Through these openings a considerable proportion of the rain may reach the subsoil without having done any considerable amount of work in removing soluble matters. There are in consequence, at a moderate distance below the surface, two distinct kinds of drainage water; one, the discharge from the general mass of soil lying above; the other consisting of water which has come directly from the surface through the channels we have just mentioned. The last-named discharge only occurs while rain is actually falling, or for a short time afterwards. The water from these two sources may have a very different composition. In the case of the drainage waters yielded by the heavy loam at Rothamsted, the distinction between these two kinds of drainage water is very plainly marked.

During March and April 1879 the quantity of nitrates was daily determined in the drainage from the deepest drain-gauge at Rothamsted, containing 5 ft. of a natural, undisturbed, field

soil (see p. 89). When no rain had occurred, the daily discharge from the soil was small in quantity, and contained very uniformly about 15 parts of nitrogen as nitrate per million of water. This dry weather discharge would clearly be derived from the lowest layer of saturated soil in the drain-gauge. When however rain occurred in any considerable quantity, the strength of the drainage water immediately fell, and only 10, 9, 8, or 7 parts of nitrogen as nitrate were found in a million of water. The next day of dry weather found however the strength of the drainage water nearly re-established. The considerable weakening of the drainage water during, or immediately after rain, was thus not due to a washing out of the whole mass of soil, but to a temporary dilution of the previous discharge with water of a different composition.

We will now give some further illustrations taken from the facts observed when studying the drainage waters obtained from the drain-pipes underlying the plots in Broadbalk wheat field at Rothamsted (*J. Roy. Agri. Soc.* 1882, 15). These plots are 8¼ yards wide, and are of considerable length. Under the whole length of each plot lies a drain pipe, about 2½ feet below the surface. The lower ends of these drain-pipes are uncovered, so that samples of the drainage waters can be at any time obtained. The soil, as elsewhere at Rothamsted, is a heavy loam. Below the subsoil of the field lies the chalk. There is thus a good natural drainage, and the water level in the subsoil probably never rises to the drain-pipes, which are supplied with water from above.

The waters collected from these pipes display remarkable alterations in composition in different stages of the same running. We shall find that these alterations are easily

understood if we take into account firstly, that the salts in a soil are not equally distributed throughout it, but lie in bands, the position of which may vary greatly; and secondly, that the pipes are fed by two distinct kinds of drainage water, one reaching them directly through channels from the surface, the other consisting of the discharge of the saturated soil.

The first discharge from the drain-pipes after the commencement of heavy rain will consist largely of water brought directly from the surface through channels in the soil, and water from this source will form a large part of the discharge so long as rain continues to fall. When, however, rain has ceased, this supply of water to the drain-pipes will soon disappear. The pipe, however, continues to run in diminishing quantity for several hours, the discharge being derived successively from lower and lower layers of soil, till all the soil lying above the pipe is exhausted, when the running comes to an end.

The first and last running of the drain-pipe thus consists of water having a totally distinct source. The relative strength of these two kinds of drainage water depends entirely upon circumstances. When the surface soil is richest in soluble salts—as when active nitrification has taken place, or a dressing of saline manure has been applied—the first discharge from the pipe may be much stronger than the last. If, on the other hand, the surface soil has been more or less washed out by previous rains, or the salts applied have spread by diffusion, then the under soil becomes the part containing most saline matter, and the discharge from the drain-pipe consequently increases in strength as its flow diminishes. This is, in fact, the condition most usually present. The discharge during very heavy rain is generally

much weaker than that produced by ordinary showers, owing to the large amount of little altered rain water which then gains access to the drain-pipes.

As a first illustration, showing the more ordinary relation of the first and last runnings of the drain-pipes in Broadbalk field, we may compare the composition of the waters collected on the evening of June 2, 1879, about one hour after the pipes had commenced running, with that of the waters collected on the following morning when the pipes had nearly ceased to run.

Table XXXIV

CHLORINE AND NITROGEN AS NITRIC ACID IN DRAINAGE WATERS COLLECTED NEAR THE BEGINNING AND END OF A RUNNING, IN PARTS PER MILLION

Plots.	Manuring.	Evening, June 2.		Morning, June 3.	
		Chlorine.	Nitrogen as Nitrates.	Chlorine.	Nitrogen as Nitrates.
3 & 4	Unmanured	0·8	none	2·3	0·9
5	Mixed Ash Constituents . . .	0·6	none	3·1	1·5
6	200 lb. Amm. Salts & Ash Cons.	12·6	0·9	23·6	4·0
7	400 lb. ,, ,, ,, ,,	22·3	3·0	43·0	6·5
8	600 lb. ,, ,, ,, ,,	38·9	9·3	58·4	13·8
9	550 lb. Nit. Sodium & Ash Cons.	2·2	12·0	7·6	31·7
10	400 lb. Ammonium Salts . . .	34·8	16·2	61·4	25·7
11	400 lb. Amm. Salts & Superphos.	37·1	10·7	66·9	18·6
12	Ditto, ditto, with Sulph. Sodium	35·8	7·8	59·8	13·3
13	Ditto, ditto, with Sulph. Pot. .	33·9	4·3	63·1	7·9
14	Ditto, ditto, with Sulph. Mag. .	34·6	7·3	43·3	10·5
15	400 lb. Amm. Salts & Ash Cons.	4·5	3·2	12·1	7·9
17	Mixed Ash Constituents . . .	2·5	none	7·3	1·5
18	400 lb. Ammonium Salts . . .	29·7	3·9	56·7	7·7

The drainage waters from the different plots are seen to differ much in composition, the differences being chiefly deter-

mined by the kind of manure applied, but in every instance the water collected at the end of the running contains a much larger proportion of chlorides and nitrates than the water collected shortly after the running commenced.

In Table XXXV we have a selection from the analyses made of the drainage waters furnished by two plots in Broadbalk field during the wet season, 1879. 400 lb. of ammonium salts per acre, consisting of equal parts chloride and sulphate, had been applied as a top-dressing on March 12; there was thus at first a great supply of soluble chlorides at the surface, while the nitrification of the ammonia afterwards enriched the surface soil with a liberal supply of nitrates.

The first running of the drain-pipes occurred on April 7. The first collection was made about one hour after the beginning of the running; the collection of the water was repeated every hour till the running ceased. No rain fell during the collections. With a surface soil rich in soluble salts, the results are quite different from those shown in the previous table; the earliest collection of water is now much the strongest, and the proportion of chloride and nitrate in the drainage water steadily diminishes to the end of the running.

The next running took place on April 13. It will be noticed that the first collection of drainage water was considerably stronger than the last of the collections on April 7, the water being now again supplied by the upper layer of the soil. The diminution in the strength of the water as the running comes to an end is less marked in the case of the chlorides than on the previous occasion, these salts being now more evenly distributed throughout the soil; but it is strongly marked in the case of the nitrates, which are still being formed in the surface soil.

TABLE XXXV

ALTERATION IN COMPOSITION OF DRAINAGE WATERS DURING THE COURSE OF THEIR RUNNING, PARTS PER MILLION

Date of Collection.	Plot 12.		Plot 13.	
	Chlorine.	Nitrogen as Nitric Acid.	Chlorine.	Nitrogen as Nitric Acid.
1879.				
April 7, 7 a.m. . . .	83.4	25.4	101.4	29.4
„ 8 „ . . .	68.6	...	83.6	...
„ 9 „ . . .	58.8	18.2	70.0	20.1
„ 10 „ . . .	53.4	...	62.2	...
„ 11 „ . . .	50.2	14.6	57.8	16.1
„ noon	47.0	...	54.4	...
„ 1 p.m. . . .	43.4	12.6	50.0	14.0
„ 2 „ . . .	40.0	...	45.4	...
„ 3 „ . . .	37.6	11.2	43.8	...
„ 4 „ . . .	...	...	41.2	11.5
April 13, 2 p.m. . . .	65.0	26.9	79.0	34.2
„ 4 „ . . .	59.0	21.2	66.2	23.9
„ 6 „ . . .	54.4	18.2	60.2	20.7
May 29, 7 a.m. . . .	68.7	16.9	67.3	9.9
„ 10 „ . . .	73.3	17.6	76.0	13.4
„ 1 p.m. . . .	68.6	17.2	63.8	16.6
„ 4.45 p.m. . .	62.3	16.2	65.1	12.5
July 1, 10 a.m. . . .	21.7	1.7	22.9	0.5
„ noon	30.1	2.1	23.6	0.5
„ 2 p.m. . . .	33.1	2.9	34.7	0.9
„ 4 „ . . .	35.7	2.9	32.6	0.7
„ 6 „ . . .	36.2	3.4	30.6	0.4
„ 8 „ . . .	36.8	3.5	36.7	0.9
August 3, 8 a.m. . .	16.2	0.6	18.4	none
„ 10 „ . .	20.2	0.2	20.8	0.2
„ noon . . .	22.6	0.6	23.1	none
„ 4 p.m. . .	22.7	0.6	25.3	0.4
1880.				
February 17, 8 a.m. .	19.9	23.3	20.7	20.2
„ noon . .	21.2	23.3	23.0	22.1

The next running occurred on May 29. The second and third collections are in this case the strongest. The principal band of salts is now no longer at the surface, but it is still distinctly above the level of the drain-pipes. The nitrates are now diminishing in quantity, owing to their consumption by the growing wheat crop.

At the next running on June 2 (see Table XXXIV) the previous order has become reversed; the last running from the pipes is now the strongest both in chlorides and nitrates, the soil surrounding the pipes being now richer in these salts than the upper layers. The same order is from this date maintained throughout the rest of the season.

It is of course quite possible that the various salts present in a soil may be distributed in a different manner, and that the chief band of one may occupy a different position from the chief band of another. We have already pointed out that the wide differences which exist in the rates of diffusion must tend in some cases to separate the various salts within a soil. The nitrates will be found very commonly to hold an independent position, as a continual production of these salts near the surface of the soil takes place, especially in showery summer weather.

A marked instance of the different position of the chlorides and nitrates in a soil is supplied by the analyses of the drainage waters from Plot 15 in Broadbalk field collected on November 15 and 16, 1880. The plot had received 400 lb. of ammonium salts (mixed chloride and sulphate) on October 25; heavy rain followed from the 26th to the 29th. The chlorides had thus been washed into the lower layers of the soil before any considerable amount of nitrification had taken place. The drain-pipe next ran on November 15.

The surface soil was now rich in nitrates, while the chlorides occupied a lower level. We find in consequence that the nitrates diminished greatly in the drainage water as the running from the pipe began to lessen, while the chlorides largely increased. The composition of three successive collections of the drainage water was in parts per million as follows:—

		Nitrogen as Nitrates.		Chlorine.
November 15, 4 p.m.	...	67.8	...	39.0
„ 16, 8 a.m.	...	50.0	...	60.6
„ 16, 2 p.m.	...	34.6	...	63.1

Alkali Lands. On large tracts of land in many portions of the earth's surface the quantity of soluble salts in the surface soil is so considerable as to greatly hinder, or frequently prevent, the use of the land for agricultural purposes. These alkali lands occur only in climates having a hot summer, and a small annual rainfall. When the rain which falls is all evaporated from the surface of the soil, and no regular percolation downwards into a drainage outfall takes place, the conditions are present which favour the production of alkali lands.

Alkali lands occur to a large extent in Northern India, in Australia, in Northern Africa, and in the western parts of North and South America. In Europe they are found to a more limited extent in Hungary. The condition of such lands, and their proper mode of treatment, has been made the subject of special study by Professor Hilgard and his colleagues at the Agricultural Experiment Station of the State of California. The information we proceed to give is taken almost entirely from the Reports of this Station for 1890–5.

The limits of rainfall within which alkali lands are found

vary with the other associated conditions. In the great Californian valley, with a rainfall varying in different parts between 34 and 6 inches, alkali lands are met with only where the rainfall is below 20 inches. In the North-West Provinces of India, alkali lands are found with a rainfall as high as 24–28 inches. The rain in these two localities is however very differently distributed. In California the rain nearly all occurs between November and April; it falls thus in the cooler portion of the year, when least is lost by evaporation; its whole effect is also concentrated into a few months. Under these circumstances the rain produces the greatest amount of percolation through the soil which is possible under the circumstances. In India, on the other hand, half the rain falls as a torrent in July and August, the greater part of which runs off the surface instead of penetrating the soil; while the remainder of the rainfall is distributed throughout the rest of the year. The same amount of rain thus produces a smaller amount of percolation in the Indian than in the Californian climate.

The texture of the soil has also a considerable influence on the production of alkali land. In a coarse-grained soil, having little power of retaining water, a considerable amount of percolation may occur even with a small rainfall; in such a soil there will also be little return of saline solutions to the surface by capillary action. In a soil composed of fine particles both conditions are reversed. Percolation is here diminished; the rise of salt solutions to the surface by capillary action in dry weather also becomes more considerable; the conditions are thus far more favourable for the accumulation of saline matter in the surface soil. The occurrence of a pan in the subsoil, preventing or hindering

the downward passage of water, is not unfrequently a further condition determining the formation of an alkaline soil.

On land moderately affected by alkali it is possible to start the growth of crops at the close of the wet season, and the crop at first grows with great luxuriance; but as summer advances saline matter accumulates at the surface, and the crop withers, or yields but a stunted produce. Cereal crops are particularly liable to injury. When the amount of alkali is still greater, the seed sown will rot instead of germinating. In the worst cases, even the natural weeds cease to grow, and the land becomes bare. A white crust or efflorescence of salts is seen upon the surface of the land in summer time. In many cases also circular depressions appear, destitute of plant growth, and characterized by a blackish colour.

Cases may now and then occur in which the source of the alkali salts can be traced to some saline formation in the neighbourhood, from which they have been transported to the soil affected; but in the majority of cases the salts found in the soil have been derived from the soil and rain alone. The salts, in fact, result from the accumulation in the soil of the products of its own decomposition, plus the saline matters brought by rain. Alkali lands are thus the natural result of an arid climate, in which the rainfall is insufficient to remove the annual production of soluble salts in the soil. The formation of alkali land is of course however much favoured when, as in the case of the Yellowstone Valley in Montana (*Soils*, *Bulletin* 14), the rocks of the district, even in their undecomposed condition, contain much gypsum and soluble salts of sodium and magnesium.

The soluble salts occurring in alkali lands are very various.

They are chiefly made up of salts of sodium, but occasionally salts of potassium and magnesium are present in considerable quantities. Chloride of sodium, though always present, very seldom preponderates as in the case of soils which owe their salinity to sea water. The most characteristic salts are sodium sulphate and sodium carbonate. When the former is the main constituent, the salt is termed in America 'white alkali'; when the sodium carbonate is present in considerable quantity the term 'black alkali' is made use of. The latter term is naturally suggested by the black colour of the soil in the spots where this salt is concentrated; the colour is due to the solution of the humus of the soil by the sodium carbonate.

The white alkali is far less injurious than the black. Of the three salts named, plants appear to be most tolerant of the sodium sulphate, while the carbonate is much the most pernicious, causing the bark of the plant stems to rot as soon as it appears on the surface. The sodium carbonate has also a very injurious effect upon the physical condition of the soil when the soil contains clay, causing it to shrink in bulk, become extremely sticky, and dry into a stony mass; the cause of this action we have already noticed (pp. 32, 34). The presence of ·08 per cent. of sodium carbonate in a heavy soil is sufficient to make it quite untillable. The very injurious action of sodium carbonate on the humus of the soil has been already referred to.

The origin of the sodium carbonate is in some cases due to the weathering of mineral silicates, as for example soda felspar, in the soil. Hilgard, however, believes that its most usual source is to be traced to a reaction between sodium sulphate and the calcium or magnesium carbonate in the soil.

According to his experiments, communicated to the American Society for the Promotion of Agricultural Science in August, 1888, no reaction takes place between these salts unless carbonic acid is also present[1]. The sodium carbonate is usually most abundant in heavy soils, and in low moist localities.

The origin of the sulphates is attributed to the oxidation of pyrites, or by some writers to the occurrence of gypsum in the original rock. The possible accumulation of the sulphates supplied by rain water does not seem to have been considered.

The three sodium salts forming the principal constituents of the soluble matter in alkali soils can hardly be reckoned as plant foods, even under circumstances thoroughly favourable to the growth of plants. With these, however, there is always associated some salts of potassium, some nitrates, and not unfrequently soluble alkali phosphates. Alkali lands are thus, generally speaking, exceedingly rich in soluble plant food, and display a high degree of fertility when the special hindrances to plant growth are removed. According to Hilgard, potassium salts amount to 3–10 per cent. of the total salts extracted by washing from the alkali soils of

[1] This question requires to be further elucidated. We shall see presently that a reverse action readily occurs, and that gypsum is applied with great advantage to land contaminated with sodium carbonate, and without difficulty converts the carbonate into the far less injurious sodium sulphate. Are we to assume that the result of the reaction in question is determined by mass; and that when calcium carbonate preponderates sodium carbonate is formed, while when calcium sulphate preponderates the reaction is reversed? If this is so, the quantity of gypsum which must be applied to a soil to effect the permanent removal of sodium carbonate will be found much larger than is at present supposed. The removal from the sphere of the reaction of any one of the products would suffice to determine a continuance of the course of change in the same direction.

California and Montana. Nitrates are more abundant in white alkali soils than in soils containing black alkali. The quantity is sometimes very large. In one of the alkali soils at the Tulare Experiment Station, Hilgard found 4,300 lb. of sodium nitrate per acre in the surface foot of soil. Sodium phosphate is chiefly found in soils containing black alkali. Sulphate of magnesium is a common constituent of the salts of the Yellowstone Valley. Analyses of some typical alkali salts will be found in Table XXXVI.

TABLE XXXVI

PERCENTAGE COMPOSITION OF SOME TYPICAL ALKALI SALTS (HILGARD)

	Kern Co., California.	Meagher Co., Montana.	Kittitas Co., Washington.	Tulare Co., California.
Potash	5.14	1.18	9.58	1.76
Soda	86.99	39.56	45.59	38.39
Lime	0.15	2.86	0.03	...
Magnesia	0.23	1.31	0.07	...
Ferric Oxide and Alumina	0.30	...	0.04	...
Sulphuric Acid	51.23	34.97	0.09	13.20
Chlorine	0.29	15.40	0.99	7.40
Carbonic Acid	0.23	1.19	34.93	11.62
Nitric Acid	...	5.37	...	10.50
Phosphoric Acid	0.09	...	1.05	1.05
Silica	1.34	0.05	0.82	...
Organic Matter and Water	4.07	1.29	7.03	17.32

The analysis in the left-hand column shows a salt consisting almost wholly of sulphate of sodium, with some sulphate of potassium. The next analysis exhibits the presence of sodium chloride, with sodium nitrate. Following this we

have the composition of a black alkali, consisting almost wholly of sodium and potassium carbonate. The last analysis refers to a salt of mixed character, extremely rich in nitrates.

The proportions in which the different salts occur at various depths, and at various times, in alkali lands, do not appear to have been as yet studied in relation to the known laws of diffusion; there is much however in many of the particulars noticed which seems to find its proper interpretation in the different rates of movement belonging to different salts, to which we have already called attention. Thus on reviewing the analyses of the salts obtained from different depths of soil in summer time, we almost always find a much larger proportion of potassium salts, of chlorides, and of nitrates in the salt obtained by extracting the soil near the surface, than in the salt extracted at the same time from a depth of 3 feet. The alkali carbonates are, on the other hand, generally far more abundant in the deeper soil. Now we have already seen that potassium salts will move more quickly in a moist medium than salts of sodium, and that chlorides and nitrates are much more diffusible than sulphates and carbonates. Again, in the *California Station Report*, 1892–3–4, 141, we have analyses of the salts found at different points across an alkali patch; here we find the proportion of potassium salts and of chlorides twice as great near the circumference as at the centre, while the proportion of sodium carbonate is greatest at the centre, and diminishes gradually towards the edge. The sulphates do not in this case march with the carbonates. Much light will probably be thrown on some of the phenomena of alkali lands, by bearing in mind the relative rates of movement of the various salts concerned.

In speaking of the proportion of alkali salts which is sufficient to cause injury, we must regard in the first place the proportion in the surface soil, as it is here that the actual injury is generally done. It is indeed exceptional for the proportion of soluble salts in the subsoil to be so great as to be productive of much harm. It is when the salts are highly concentrated by the evaporation of their solution on the surface of the soil that active mischief takes place.

In Table XXXVII are given some determinations of the quantity of alkali salts found in land of known fertility belonging to the Experiment Station at Tulare, California. The salts in the first three inches of the soil, and in the first foot, were extracted and analysed. The results found would doubtless have been still more striking if the composition of the first inch had been ascertained.

The land growing a good barley crop is seen to have contained on March 31, 0·178 per cent. of soluble alkali salts in the first three inches of soil; the barley, which was probably sown in January, was then 2 ft. high. In May the proportion of alkali at the surface of the soil has nearly doubled, but at this stage of growth the presence of an excess of salts is not nearly so hurtful as when the crop is young. The barley in May was 4 ft. high, and yielded 2½ tons of barley hay per acre. The alkali on this land, though moderate in quantity, was of a particularly hurtful type, about one-half of the salts consisting of sodium carbonate.

The land on which the crop of barley was small, amounting to only one ton of hay per acre, was not examined till September, or nearly at the close of the hot weather; the results are thus not strictly comparable with those already quoted.

The soil is seen to have been extremely rich in alkali salts, which reached 1·381 per cent. in the first 3 inches at the end of the summer, or ·513 per cent. in the first foot; but the salts in this case were of a comparatively harmless character, very little sodium carbonate being present.

Table XXXVII

ALKALI SALTS IN SOILS AT TULARE, CALIFORNIA (HILGARD)

	Per cent. of Soil.				Pounds per Acre.	
	Total Alkali Salts.	Alkali Sulphates.	Alkali Chlorides.	Alkali Carbonates.	Total Alkali Salts.	Alkali Carbonates.
	Reclaimed Alkali Land, Barley Good, March, 1895.					
1st 3 Inches	0.178	0.105	0.009	0.064	1780	640
1st Foot . .	0.159	0.065	0.005	0.089	6360	3560
	May, 1895.					
1st 3 Inches	0.308	0.141	0.016	0.148	3080	1480
1st Foot . .	0.288	0.094	0.018	0.176	11530	7040
	Reclaimed Alkali Land, Barley Feeble, Sept. 1894.					
1st 3 Inches	1.381	0.694	0.350	0.008	13810	80
1st Foot . .	0.513	0.278	0.113	0.014	20520	560
	Alkali Land after Gypsum, Barley Failed, Sept. 1894.					
1st 3 Inches	2.358	1.421	0.739	0.074	23580	740
1st Foot . .	0.840	0.460	0.236	0.094	33580	3760
	Unreclaimed Alkali Land, Barley Failed, May, 1895.					
1st 3 Inches	0.773	0.251	0.144	0.351	7730	3510
1st Foot . .	0.494	0.171	0.062	0.248	19800	9930

The next soil, containing 2·358 per cent. of soluble salts in the first 3 inches, failed entirely to yield a growth of barley.

The last-named soil in the table proved equally sterile; it contained however a much smaller quantity of alkali salts than the two previously named, but these salts were very rich in sodium carbonate.

In judging the character of alkali land it is very useful, as pointed out by Hilgard, to ascertain the total quantity of soluble salts in the first 4 ft. of soil; such a figure represents in fact the whole amount which the agriculturist has at any time to deal with. On the basis of a few such determinations Hilgard concludes that the maximum quantity of alkali salts, consistent with the production of a full crop of barley hay, is from 25,000 lb. to 32,000 lb. per acre in 4 ft. of soil, the salts being supposed to contain not more than one-half their weight of sodium carbonate.

Whitney and Means, in their investigation of the alkali soils in the Yellowstone Valley, take 15,000 lb. of soluble salts per acre in the surface foot of soil as the limit of possible plant production. The salts in this case were free from alkali carbonates.

In a report on the salt lands of Habra in Algeria, Berthault and Paturel state (*Ann. agronomiques*, 1889, xv. 35) that the cultivation of the vine is not hindered by the presence of 0·06 per cent. of alkali salts in the soil. When the amount reaches 0·08 per cent. in the surface soil, and 0·27 per cent. in the subsoil, the vine languishes, and becomes unprofitable. With 0·17 per cent. in the surface soil, and 0·37 in the subsoil, the vine dies. Cereal crops yield a normal harvest with 0·20 per cent. of alkali salts in the soil. All these determinations of saline matter were made in May, when the salts had not fully

reached the surface. The salts consisted usually of nearly equal parts chlorides and sulphates; no alkali carbonates are mentioned. Soils too saline to grow cereals were capable of producing a good natural pasture.

Berthault and Crochetelle (ibid. 1895, xxi. 122) have also reported more briefly on the soils reclaimed from the sea in the Bas-Médoc, and confirmed the previous conclusion as to the amount of alkali salt which cereal crops will endure.

We have already mentioned that germinating seeds are most sensitive to the effects of alkali, the delicate root and stem first produced not being protected by any tough external covering; the seeds of leguminous plants appear to be especially sensitive. Propagation by cuttings is impossible in an alkaline soil. Plants drawing their nourishment from the surface soil are generally more affected than those having deep roots. Lucerne may often be successfully grown on alkali land. Pear trees are also noted for their resistant power. The sunflower tribe, and many of the *cruciferae* are well suited for soils of this character.

Some successful trials of sugar beet have been made in California. Hilgard and Loughridge in their Report on these experiments (*California Station Report*, 1894–5, 71) conclude that beets of good quality and purity may be grown on lands containing 12,000 lb. per acre of alkali salts in 3 ft. of soil, provided that the sodium chloride does not exceed 1,500 lb. per acre. They consider sodium chloride as more injurious to beet than sodium carbonate.

The Australian saltbush, *Atriplex semibaccatum*, is an excellent perennial fodder crop, much relished by sheep; it appears capable of growing with vigour on almost the worst

forms of alkali land (*California Station Report*, 1894–5, 319). An analysis made by Jaffa (ibid. 165) showed the dry matter of the plant to contain 20·84 per cent. of ash, about 40 per cent. of which was sodium chloride. A crop of 5 tons of dry saltbush fodder would remove 1,360 lb. of alkali salts from the soil. One mode of ameliorating alkali land is clearly to grow crops of this description, to be afterwards consumed off the soil.

Treatment of Alkali Land. The successful treatment of alkali land is a problem of great importance owing to the wide areas over which such lands occur. As they are found always in districts having an insufficient rainfall they have been largely treated by irrigation. Instead however of the salts being removed from the land by this treatment, it has often happened, both in India and California, that the systematic irrigation of a district has largely increased the extent of infertile land. Land not previously known to contain alkali has often a few years after the introduction of irrigation been found covered with patches of alkali, which have gradually extended till the whole area has become sterile. It was at first supposed that the injury thus produced was due to the presence of alkali salts in the water applied to the land; but although the composition of the water must clearly have an influence on the result, the existence of alkali salts in the water used for irrigation is no sufficient explanation of the injurious results which follow this treatment, for a similar injury is also observed where a perfectly pure water has been employed. The injury thus produced by irrigation is commonly, and accurately, described as due to a 'rise of the alkali.'

To understand the effect produced by irrigation, or to establish any rational treatment of alkali lands, we must be

acquainted with the position and movements of the injurious salts within the soil; in this study of the subject, the facts already laid down in the earlier part of the present chapter will find fresh illustration.

The first point we have to bear in mind is that the injurious salts are generally confined to a few feet of the soil. This fact appears in the numerous examinations of alkali land to the depth of 4 ft. made in California, and further evidence on the subject is supplied by the purity of the water in the deeper wells sunk in the same district[1]. We have thus to deal with a limited quantity of alkali salts; and the first and great lesson we have to learn, is that the injurious effect of these salts depends entirely on *their position* in the soil.

In 1895 determinations of the quantity of alkali salts in each successive three inches of soil were made in the case of certain typical lands forming part of the Experiment Station at Tulare, California; some of these determinations will be found in Table XXXVIII.

The unirrigated natural soil mentioned in this table was one not under cultivation; it was covered in the spring with a luxuriant natural growth of flowers, chiefly annuals, which died down in summer time during the heat and drought usual in that climate. The results of the examination of this soil show that in May the soluble salts formed a well-marked band, the greatest concentration of the salts occurring between 30 and 33 inches below the surface; above and below this point the quantity of salts rapidly diminished. The distribution of the salt in this soil at once reminds us of the

[1] In recent investigations in the Yellowstone Valley the subsoil was found impregnated with salts to a much greater depth than in California.

Table XXXVIII

POUNDS OF ALKALI SALTS PER ACRE AT VARIOUS DEPTHS, TULARE, CALIFORNIA (HILGARD)

	Natural Soil, Unirrigated.		Bare Land, Irrigated 4 Years.
	May 3, 1895.	September, 1895.	May, 1895.
0 to 3 Inches	220	260	7730
3 ,, 6 ,,	130	160	4490
6 ,, 9 ,,	220	200	4360
9 ,, 12 ,,	240	240	3180
12 ,, 15 ,,	350	540	3320
15 ,, 18 ,,	950	1170	2860
18 ,, 21 ,,	1690	1970	2230
21 ,, 24 ,,	1470	2480	1090
24 ,, 27 ,,	2620	3200	800
27 ,, 30 ,,	4910	4610	580
30 ,, 33 ,,	5290	5120	400
33 ,, 36 ,,	4260	3000	360
36 ,, 39 ,,	2240	1100	340
39 ,, 42 ,,	1140	680	190
42 ,, 45 ,,	810	450	230
45 ,, 48 ,,	490	240	270
Total 4 Feet	27030	25420	32430

	Reclaimed Land Growing Good Barley.		
	March 31, 1895.	May, 1895.	September, 1895.
First Foot	6360	11530	8660
Second ,,	10240	9850	3950
Third ,,	3520	3090	1730
Fourth ,,	1080	...	970
Total 4 Feet	21200	24470	15310

perfectly similar band of salt occurring in the soil of the laboratory experiment, the results of which have been already given in the Table on p. 202. The salt in this alkali land owes its position to the winter rains; these, as already mentioned, occur from November to March. These rains have been sufficiently continuous, and sufficient in quantity, to carry the greater part of the salts to the depth indicated; and the salts have afterwards gradually spread upwards, partly by diffusion, and still more by the movement of water towards the surface as a consequence of summer evaporation.

The soil in question was examined next in September. The results given in the table show that a distinct, but not a great movement of the salts towards the surface has taken place since the examination in May. As soon as a soil becomes dry, all movement of salt will of course cease. In the case of this soil it is clear that the alkali is doing a minimum amount of injury; the main portion of it does not reach the surface even at the end of the summer.

In the case of the reclaimed land growing good barley, mentioned at the foot of Table XXXVIII, we have a further illustration of the position which the band of salts occupies in the soil in March shortly after the rains have ceased, and of the higher place which it takes as summer advances. The differences in the total quantity of salts found at the three dates of sampling this soil must not be insisted on, as the distribution of the salts in alkali land is always more or less irregular, depending largely on differences in the physical character of the soil.

By the side of the results furnished by the natural soil in Table XXXVIII will be found the results obtained at the same time from a soil of similar character which had been

irrigated for four years, but was now without a crop. An inspection of the table shows at once that the irrigation has brought about a veritable rise in alkali. The soil, as before, contains a well-marked band of salt, but this band has moved to the surface. The first foot of soil now contains 19,760 lb. of alkali salts per acre, an amount sufficient to make the growth of ordinary crops impossible.

No information is given as to the mode of irrigation adopted in this instance, whether flooding of the land, or the supply of water without flooding by means of channels or shallow ditches; both modes of irrigation are apt however to produce the same final result, unless special precautions are taken.

In the case of land irrigated by the soakage of water from channels running through it, it is clear that a rise in the water level in the subsoil must occur; and as a fact it does occur to a large extent. In the Yellowstone Valley the natural water level in the subsoil is at least 20 feet below the surface. Irrigation from a high-level canal has raised this water level in many places to within 3 feet of the surface, while the lower parts of the irrigated district have been converted into a swamp. It is evident that a rise of the subsoil water must bring the salts in the soil to the surface. We have here in fact another instance of the action already several times described in the course of this chapter, only in the present case the movement of the water is upward instead of downward.

Although a concentrated salt solution may be brought to the surface by the displacing action of fresh water, the salts would not remain accumulated here were it not for another action, which has in fact a preponderating influence on the question before us. The large amount of evaporation which

takes place from a wet soil during summer in such climates as those of India or California, determines a rapid concentration of the salt solution at the surface, resulting often in the crystallization of the salt, and the covering of the soil with a white crust. While however the soil beneath continues moist, the salt accumulating at the surface will spread by diffusion downwards, or be more rapidly carried in this direction by rain. The soil is in this manner enriched with salt from the top, and a band of salt is formed below the surface as shown in the right-hand column of Table XXXVIII.

The irrigation of land by temporarily flooding the surface with water was naturally at first regarded as an excellent plan for removing alkali from the soil. In the case of a soil provided with good natural or artificial drainage, the liberal application of water at the surface, and its percolation through the soil to the drainage outfall, would doubtless prove the most effectual method which could be devised for freeing the soil from alkali. Irrigation systems in India and California have however been carried out without any provision being made for drainage. The soils dealt with have also frequently been of a close texture, slowly permeable to water; and hard pans, still more impervious to water, frequently occur two or three feet beneath the surface. Under these circumstances surface flooding produces no permanent benefit, and shortly after it has ceased the accumulation of alkali at the surface takes place as actively as before. Both in India and California large districts have been irrigated from high-level canals, without any provision being made for drainage from the soil; the result has been that the water level has been brought nearly to the surface of the land, and some of the lower lying fields converted into swamps. With this rise of

subsoil water, the formation of alkali crusts on the surface during summer drought has considerably increased, and in many cases land is now far less fertile than it was before the expensive irrigation systems were introduced. We may lay it down then as a general rule that irrigation, as ordinarily practised, is a very unsuitable treatment for alkali lands, unless free drainage is at the same time established through the soil.

There are several ways by which the fertility of an alkali soil may be considerably improved. When the land is contaminated with salts containing sodium carbonate, it is quite possible by applications of gypsum to convert this into sodium sulphate, which we have seen is far less harmful to crops. Where gypsum can be obtained at a moderate cost, it is often possible to reclaim land from sterility by this application only, and this has been actually done to a considerable extent in California. In India, unfortunately, gypsum is frequently not easily obtained. The gypsum should be applied in dressings of from 500 lb. to 1 ton or more per acre. On unirrigated land the application will probably succeed best when applied just before the commencement of the wet season. Gypsum has no action on sodium carbonate in a dry soil. Where gypsum is costly, it may be usefully spread in smaller quantity shortly before sowing the seed, thus protecting the young plant in its tenderest condition; or local applications may be made to alkali patches, or round the roots of fruit trees. The effect of gypsum is seen in the greatly improved tilth of the land, as well as in the absence of the corrosive action on plant tissues.

Gypsum may sometimes be of great use for the destruction of the hard pan common in alkali lands. On a calcareous hard pan it has no effect. In soils containing much sodium

carbonate there is however a special kind of pan, which forms at the depth to which the alkali salts are annually brought by the winter rains. In the natural unirrigated soil mentioned in Table XXXVIII such a pan occurs at about 32 inches below the surface. This pan is due to an accumulation of the finest clay washed down by rain, and hardened by the action of the sodium carbonate. Under the influence of water and gypsum such a pan is effectually disintegrated. To accomplish such a task the gypsum must of course be applied in excess.

The remedial measures of the most general application have for their object the diminution of surface evaporation during summer, and consequently the prevention of the rise of the band of alkali. As already mentioned, if the alkali can only be kept in the moist subsoil it is comparatively harmless; it is when concentrated by evaporation at the surface that it becomes so fatal to plants.

To reclaim alkali land, the soil should be deeply cultivated as soon as possible after the wet season is over, and a layer of 8 inches or more of loose soil should be maintained at the surface all through the summer. Under these circumstances the amount of water evaporated by the soil is much diminished; the alkali will also fail to reach the surface, its progress being stopped by the loose dry soil. The rains of the next wet season will now carry the salts to a lower level than before. This treatment may be repeated, and a further lowering of the salt band obtained, till the full effect possible from the winter rains is reached. The land is now cured, if afterwards properly cultivated. Any other plan which diminishes the evaporation at the surface will act in a beneficial manner, as for instance mulching the surface

with straw; but deep cultivation as soon as the wet season is over is the most effective plan, as a considerable layer of soil is by this means at once saved from the invasion of the alkali.

It is interesting to note that the plans just mentioned, which commend themselves so thoroughly to modern views and accurate knowledge, are precisely those adopted by the Hindoo cultivator. In a letter on the subject of alkali lands, sent to me in 1884 by Major D. G. Pitcher, Assistant Agricultural Director for Oudh, he says:—

'Where the soil is "Oosur," or simply barren and not efflorescent with salts, I do not think it will pay to attempt to render the land fertile other than in the way the natives in some parts do themselves; and that is to raise a boundary round a small plot so as to keep the rain water on it, and to go on tilling it again and again each year in their spare time until it bears something; once it begins to bear it goes on improving. Again, where there is efflorescence, they find that in certain localities covering the ground with straw for two or three years restores its fertility.'

When alkali land has been reclaimed by the means indicated, and the band of salts has been lowered as far as possible, the subsequent cultivation must of course be such that the benefits gained are not afterwards thrown away. The point to be always kept in view is the adoption of summer tillage, and of any other means which may reduce to the lowest point the evaporation from the surface. Crops which admit of being hoed between the rows during summer, present, as Hilgard points out, many advantages. Another class of crops well suited to alkali lands are those shading the surface with thick foliage, and possessed of deep roots. Lucerne excellently fulfils these conditions. In land covered

with such a crop, the water is evaporated through the plant, and not to any considerable extent from the surface of the soil.

Alkali land when suitably treated is remarkable for yielding good crops with a small rainfall; the presence of alkali becomes indeed a distinct advantage in an arid climate. Hilgard explains this as due to the greater hygroscopic character of the soil, but he quotes no facts bearing out this opinion. We have already seen (p. 117) that the presence of encrusting salts much diminishes the rate of evaporation from a soil's surface. Probably, however, the main effect of a copious supply of salts in the soil is to diminish the amount of evaporation from the plants growing on it, and to render a small supply of water sufficient for their needs.

The very important question of the proper mode of applying water to alkali lands during the dry season is not apparently as yet practically solved. The breaking up of pans, and the provision of efficient drainage, would of course enable water to be freely applied without any danger of its being followed by a rise of alkali. Such treatment, apart from its expense, would however entail the loss to the soil of the large quantities of available plant food which the alkali salts contain; it is not therefore to be hastily recommended.

Hilgard has suggested a system of sub-irrigation by means of pipes; the water to be used in such moderate quantity, and delivered at such a distance below the surface, that no rise of a solution of alkali salt to the surface need be feared. Such pipes might also be used at other times of the year for drainage purposes. The scheme has not apparently been tried.

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